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REPORT OF THE COMMITTEE ON A TREATISE ON MARINE ECOLOGY AND PALEOECOLOGY

1947 - 1948

HARRY S. LADD, CHAIRMAN

VICE-CHAIRMEN:

GORDON GUNTER, FOR BIOLOGY
KENNETH E. LOHMAN, FOR GEOLOGY
ROGER REVELLE, FOR OCEANOGRAPHY

Division of Geology and Geography
National Research Council
Washington, D. C.

NATIONAL RESEARCH COUNCIL
2101 Constitution Avenue
Washington 25, D. C.

December 1948

NATIONAL RESEARCH COUNCIL

DIVISION OF GEOLOGY AND GEOGRAPHY

WASHINGTON, D. C.

* REPORT OF THE COMMITTEE ON A TREATISE ON MARINE ECOLOGY AND PALEOECOLOGY

1947 - 1948

Presented in preliminary form as Appendix H
at the Annual Meeting of the Division
April 24, 1948

* (No. 8 in this Series. See page 117
for list of previous reports.)

COMMITTEE MEMBERS (1948)

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Gordon Gunter, Vice Chairman for Biology
Kenneth E. Lohman, Vice Chairman for Geology
Roger Revelle, Vice Chairman for Oceanography

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REPORT OF THE COMMITTEE ON

TREATISE ON MARINE ECOLOGY AND PALEOECOLOGY

INTRODUCTION

No formal Committee meetings were held during the year but with half of the Committee resident in Washington there were many informal meetings within this group; two non-resident members were visited in the field and several others made trips into Washington. On May 12, 1948 a paper by Kenneth Lohman entitled "Paleoecology, an integral part of Paleontology" was read before the Geological Society of Washington.

One new member has been added to the Committee, Dr. Frank C. Whitmore, Jr. of the U. S. Geological Survey.

TREATISE ON MARINE ECOLOGY AND PALEOECOLOGY

GENERAL

Considerable progress has been made during the year in the preparation of the proposed treatise. Part One is to deal with ecology and will be written jointly by the biologists and the oceanographers. No sections of this part have been completed but final arrangements have been made for Vice-Chairman Gunter to spend six months, starting November 1, 1948, at the Scripps Institution, working with oceanographers on this section of the Treatise. These arrangements have been made through Dr. Roger Revelle, Vice-Chairman for Oceanography, who is now Associate Director at Scripps. Dr. Gunter will also visit the Woods Hole Oceanographic Institution, and it is hoped that a rough draft of the first part of the Treatise will be completed next year.

In Part Two of the Treatise which deals with paleoecology, there has been one addition to the "Selected analyses from the geologic record" as listed in last year's report: Heinz A. Lowenstam will contribute an analysis of Silurian coral reef ecology in the Mississippi Valley region. Dr. Christina Lochman Balk, who is preparing a report on the Cambrian assemblages of the Rocky Mountains, will be assisted by Mr. Charles Bell.

Included in the present report is a paper by Preston Cloud and Virgil Barnes dealing with paleoecology in Ordovician times in the Llano area of Texas. This paper is enlarged and modified from a version published in Annual Report No. 6. It contains all the material for a finished chapter of the Treatise and the Committee feels justified in publishing this version as it will serve as a guide to others who are writing up "Selected Analyses". Parts of the general discussion in the Cloud-Barnes paper will probably be incorporated in the introductory sections to the paleoecological part of the Treatise.

The Committee has decided that all chapters of the Treatise, including the individual sections of the annotated bibliographies, will be signed by the individuals preparing them with the Committee reserving the right to edit all contributions to achieve continuity and uniformity of style. Four sections of the Annotated Bibliographies, two dealing with Nautiloid Cephalopods by Dr. H. B. Stenzel and two with Birds by Dr. Herbert Friedmann, are included in the present report.

It is urged that all contributors to the annotated bibliographies follow the form of citation used in the U.S.G.S. Bibliography of North American Geology. Serials not commonly cited in the above bibliography present a problem, to be sure, but the form of citation can be followed with little difficulty. Thus, Proceedings, Transactions, Bulletins, etc., follow the name of the Society or other organization rather than precede it. If the large number of contributors to the Treatise do not follow a uniform procedure, the necessary editorial work will become prohibitive.

K. O. Emery and K. E. Lohman, who will be largely responsible for selecting illustrations for the Treatise, have begun assembling material; a number of photographs of the ocean bottom have been contributed by Dr. Francis P. Shepard.

LIST OF ASSIGNMENTS FOR ANNOTATED BIBLIOGRAPHIES

Marine ecology: With one exception all of the assignments in this bibliography have been made. Four of the twenty-four assignments have been completed. A complete list of the assignments is given below.

Plants	
Diatoms	K. E. Lohman
Algae	R. H. Williams
Other plants	R. W. Brown
Protozoa	
Foraminifera	Earl H. Myers*
Radiolaria	G. Dallas Hanna
Other Protozoa	G. Dallas Hanna
Sponges	M. W. de Laubenfels
Coelenterates	
Corals	John W. Wells
Other coelenterates	Frederick M. Bayer
Vermes	Olga Hartman
Echinoderms	(unassigned)
Bryozoa	L. W. Hutchins
Brachiopods	G. A. Cooper*
Mollusks	
Oysters	Gordon Gunter
Nautiloids	H. B. Stenzel*
Other mollusks	Willis G. Hewatt
Arthropods	Waldo Schmitt and C. H. Edmondson
Vertebrates	
Cyclostomes	Edward C. Raney
Other fish	Gordon Gunter
Amphibia	Karl P. Schmidt
Turtles	Rainer Zangerl
Other reptiles	Karl P. Schmidt
Birds	Herbert Friedmann*
Mammals	Remington Kellogg and Frank C. Whitmore, Jr.

*Assignment completed

Paleoecology: All but four assignments in this bibliography have been made. Six of the fifty-three assignments have been completed and two of these are included in the present report. A complete list of the assignments is given below.

Plants
- Diatoms ..... K. E. Lohman
- Algae ..... J. Harlan Johnson
- Miscellaneous spores and pollen
  - Paleozoic ..... James Schopf
  - Post-Paleozoic ..... L. R. Wilson
- Other plants ..... R. W. Brown

Protozoa
- Foraminifera
  - Paleozoic, other than Fusulines ..... Chalmer Cooper
  - Paleozoic, Fusulines ..... Lloyd Henbest
  - Mesozoic ..... A. R. and H. T. Loeblich
  - Cenozoic ..... W. Storrs Cole
- Radiolaria ..... A. S. Campbell
- Other Protozoa ..... G. Dallas Hanna

Sponges
- Paleozoic, other than Hexactinellids ..... Vladimir Okulitch
- Post-Paleozoic, other than Hexactinellids ..... M. W. de Laubenfels
- Hexactinellids ..... Kenneth Caster

Coelenterates ..... John W. Wells

Vermes
- Conodonts ..... Samuel Ellison*
- Other Vermes ..... B. F. Howell

Echinoderms
- Cystoids ..... G. Winston Sinclair
- Blastoids ..... Lewis M. Cline
- Crinoids ..... Lowell R. Laudon

Asteroids
- Paleozoic ..... G. A. Cooper
- Post-Paleozoic ..... Charles Berry

Ophiuroids
- Paleozoic ..... G. A. Cooper
- Post-Paleozoic ..... Charles Berry

Echinoids
- Paleozoic ..... G. A. Cooper
- Post-Paleozoic ..... C. Wythe Cooke

Holothurians ..... R. C. Moore

Bryozoa ..... Max Elias

Brachiopods ..... G. A. Cooper*

Mollusks
- Paleozoic
  - Amphineura, Gastropods, Scaphopods ..... A. L. Bowsher
  - Pelecypods ..... Carl C. Branson
  - Nautiloids ..... Rousseau H. Flower
  - Ammonoids ..... A. K. Miller
- Triassic ..... Bernhard Kummel
- Jurassic ..... Ralph Imlay
- Cretaceous ..... H. R. Bergquist
- Tertiary, Atlantic and east Gulf (except Nautiloids) ..... Julia Gardner

Tertiary, west Gulf coast (except Nautiloids) ..... H. B. Stenzel
Tertiary, West Coast (except Nautiloids) ..... W. P. Woodring*
Tertiary, Nautiloids ..... H. B. Stenzel*
Arthropods
Crustacea, other than Ostracodes ..... (not assigned)
Ostracodes, Paleozoic ..... Allen F. Agnew*
Ostracodes, post-Paleozoic ..... I. G. Sohn
Myriopods ..... (not assigned)
Arachnids ..... (not assigned)
Insects ..... W. Dwight Pierce
Vertebrates
Agnatha ..... George M. Robertson
Pisces ..... Lore David
Amphibia ..... (not assigned)
Reptiles ..... Rainer Zangerl
Birds ..... Herbert Friedmann*
Mammals ..... Remington Kellogg and Frank C. Whitmore, Jr.
Problematical fossils ..... Kenneth Caster

*Assignment completed

CURRENT ACTIVITIES

EASTERN UNITED STATES

Chesapeake Bay Institute: Johns Hopkins University, in cooperation with the States of Maryland and Virginia and the Office of Naval Research, is establishing a Chesapeake Bay Institute. The primary purpose of the laboratory will be to study the oceanographic and marine ecological problems peculiar to inland waterways such as Cheaspeake Bay and the immediate offshore areas. Particular emphasis will be placed by the two cooperating States upon fisheries and shell fisheries research problems coupled with a study of the best methods of economic conservation of such marine products. In its formative stage, the laboratory is under the direction of Dr. Charles Renn of Johns Hopkins. The permanent Director of the laboratory has not yet been chosen.

Woods Hole Oceanographic Institution: Dr. George L. Clarke and his associates are studying the nutrient requirements of diatoms and mollusks in large, out-door concrete tanks. "Similar determinations of the production rates of fundamental 'producers' and 'consumers' are being conducted in both salt water and fresh water ponds... A special study of the nutritional value of the marine zooplankton has been made to determine the organic matter represented by this important link in the food chain..."

The following studies have been under the direction of Dr. Alfred C. Redfield:

1) The study of the propagation of clams, by Dr. J. C. Ayers and H. J. Turner.
   a) "to determine the factors which effect the attachment and survival of clam larvae,
   b) to develop and study methods of planting seed clams,
   c) to determine the rates of growth and mortality under various environmental conditions."

2) Studies of the pollution of sea water and its effect on marine forms by Dr. B. Ketchum.
3) "An investigation of the ecology and chemistry of the water of the Continental shelf and slope south of Woods Hole... The objectives of this investigation have been to study the distribution of plant nutrients at various seasons and the effect of depth and the characteristics of the water masses upon the cycle of phosphorus as it is assimilated by the phytoplankton and regenerated by the bacteria."

Dr. L. W. Hutchins reports that the following studies have been undertaken:

1) "Investigations of the growth of mussels in the tunnel of the Lynn Gas and Electric Company... Length-frequency analyses were completed (some 62,000 mussels were measured). In 1948 more detailed data on the growth of about 5,000 mussels have been obtained."
2) Studies of the distribution of Bryozoa from samples collected in the Gulf of Mexico by Phleger, Stetson, and Trask.

Fred B. Phleger, Jr. and associates have the following projects on the ecology of Foraminifera underway:

1) Foraminifera from bottom samples, cores, and plankton tows from the Gulf of Mexico. It is anticipated that this work will be finished in the next few months.
2) Foraminifera from a core in the Boston basin driven to bedrock. This study has been completed.
3) Distribution of sediments and Foraminifera from over 700 bottom samples in a near-shore area in the Gulf of Maine, off Portsmouth, New Hampshire.

Gordon A. Riley has completed a general review of available literature and has prepared a report on the practical aspects of coral reef growth.

Prof. Charles C. Davis of the University of Miami is studying the plankton as a part of a comprehensive ecological survey in the Miami area.

MIDDLE UNITED STATES

Dr. M. K. Elias of the Nebraska Geological Survey is preparing a report on probable depths at which Paleozoic and Mesozoic bryozoans lived.

Mr. Heinz Lowenstam, who is assisting Dr. H. Urey with an isotope "geological thermometer" that opens fascinating possibilities in the field of paleoecology, states:

"Professor Urey at the University of Chicago has pointed out that it may be possible to measure the temperatures at which organisms of the past lived, from the isotopic composition of their fossil remains. This should be true, according to calculations, for calcium carbonate and perhaps also for silica and phosphate. The work in Dr. Urey's laboratory has progressed to the point, where a mass spectrometer gives the needed high precision, and where the preparation of carbonate samples can be made reproducible. A preliminary temperature scale has been established empirically, that is, the empirical relationship between temperature and isotopic compositions. Also, the isotope analyses, that is the

ratio of O^{16} and O^{18} of a number of calcareous fossils and their enclosing sediments from various stratigraphic positions of the Cretaceous of England, have been completed with encouraging results. Methods and results will be presented by Dr. Urey at the meetings of the American Association for the Advancement of Science in September and in more detail at the meeting of the Geological Society of America in November 1948. I am planning to present a talk on the paleobiologic implications at the meeting of the G.S.A. It has already become evident that only a small percentage of the fossil record, requiring properly selected fossils, will produce reliable results. Furthermore a detailed paleo-biological and burial environmental analytical study in conjunction with structural and mineralogical examination of the skeletal remains will always be required to assure the selection of suitable specimens. In this connection Dr. Urey and I will, in September, collect Upper Miocene assemblages from the Miocene Yorktown formation and its equivalents in the area between Florida and Virginia for our first detailed test case of the fossil record."

A recent paper on the Niagaran inter-reef formation of northeastern Illinois by Dr. Lowenstam is reviewed in this report (p. 15). He has also completed a study of subsurface distribution and facies relations of the Niagaran reefs in Illinois. The results dealing with the oil possibilities of the Niagaran subsurface reefs will be published shortly by the Illinois Geological Survey. A second paper discussing broader aspects of the environmental setting and sediment relations, including evidence as to prevailing winds, is in preparation.

According to Science, the establishment of a Marine Research Laboratory at Ocean Springs on the Mississippi Sound has recently been authorized by the Mississippi Legislature. The Laboratory is sponsored by the Mississippi Academy of Science and will be directed by R. L. Caylor of Delta State College, Cleveland, Mississippi.

Dr. Norman D. Newell has planned a comprehensive study of the paleoecology of the Permian reefs of West Texas. Field work which will include detailed mapping of ecological facies will extend over a period of years and will be preceded by studies of Recent conditions. The project is sponsored jointly by the American Museum of Natural History and Columbia University; graduate students from Columbia and other parts of the country will be included in the project. The work will be entirely financed by the Humble Oil and Refining Company.

F. W. Rolshausen of the Humble Oil and Refining Company is setting up a set of standards to enable those working with well samples to visualize ecological conditions from the sample description. His standards will include: type of material, color, tenture, fracture, fauna, estimated depth of water based on knowledge of Recent conditions.

The Texas A. & M. Research Foundation has recently set up an organization, of which Dr. A. A. Jakkula is Executive Director, to investigate the causes of oyster mortality in the bays of Louisiana and Texas. This work will be very comprehensive in scope, as indicated by the following Divisions of Research which have been established: Bacteriology, Biological Technique, Chemistry, Ecology and Hydrobiology, Geology and Hydrography, Oyster Biology, Parasitology, and Physiology. Each division has in its program much that will be of value to ecologists and paleontologists, and the findings of this Research Foundation will be watched with great interest by those working in these and related fields. A comprehensive bibliography on the oyster has been compiled at Rockport, Texas,

under a cooperative arrangement between the Foundation and the Texas Game, Fish, and Oyster Commission. A museum of oyster shells is being assembled and maintained at Grand Isle by Dr. J. G. Mackin, in which the shells are identified and catalogued and used to illustrate the effect of various types of mortality and abnormality.

Gordon Gunter of the University of Texas reports that a small oyster laboratory has recently been constructed at Port Aransas, Texas.

WESTERN UNITED STATES

Dr. Carroll Lane Fenton and Mildred Adams Fenton will spend the summer of 1948 revisiting Pre-Cambrian regions in the Medicine Bow Mountains, in Glacier National Park, and in southern Alberta. They will obtain additional material for their section of the Treatise dealing with the paleoecology of the Pre-Cambrian of the northwest.

During the current field season Prof. Siemon Muller of the Department of Geology of Stanford University has done extensive field work on facies distribution in the Triassic formations of western Nevada and California for the Geological Survey. Much of the information so gained will be used by Professor Muller in the preparation of a section on the Paleoecology of the Triassic of western Nevada for the Treatise. This will be one of the "Selected analyses from the geologic record".

At the Denver meeting of the Society of Economic Paleontologists and Mineralogists in April 1948 there were a number of papers of ecological interest. Abstracts of most of these are given below:

Symposium on Environmental Significance of Dwarf Faunas

PROTOZOA

Cecil G. Lalicker, University of Kansas, Lawrence.

It is believed the most important causes of dwarfed protozoan faunas are the kind and amount of food, presence of mud and other impurities in water, and variations in temperature of water. The variations in size and form of several living protozoans observed under sterile cultures and with controlled food are discussed. Several fossil dwarfed foraminiferal faunas which have been noted in rocks of different geologic ages are described.

BRACHIOPODA

Preston E. Cloud, Jr., Harvard University, Cambridge, Mass.

Assemblages of dimunitive brachiopods may result from any one or any combination of the following factors: (1) Actual dwarfing due to physiological retardation of growth, (2) accumulations of immature specimens of normally larger species and adults of smaller species due to segregation by moving water, and (3) accumulation of immature specimens because of environmental factors tending to produce subnormal life-span or exceptionally high mortality of the younger shells. Interpretation in any given instance is a matter of determining from the shells themselves, from careful comparison with recognizably normal assemblages of near homotaxial equivalence, and from the physical and chemical nature of the entombing sediments which factor or combination of factors is the more logical. The

paleoecological significance of assemblages of diminutive brachiopods as such is thus indirect. They merely bring attention to a situation the interpretation of which depends on a variety of physical, chemical, and biological considerations.

The brachiopod faunas of the "Tully pyrite," the "Clinton hematite," the Glen Park and Salem limestones, and the Windsor series are briefly discussed. The fact emerges that more data are needed on the ecology of recent brachiopods and on assemblages of diminutive fossils and their entombing sediments.

AMMONOIDEA

Bernard Kummel, University of Texas, Austin.

Dwarfed and/or small cephalopods have been reported from many parts of the geologic column. Data assembled from preliminary studies of the Cretaceous pyritic micromorph faunas of Texas and from an Upper Triassic (Norian) fauna from the Cordillera Central of northern Peru will be given. Both of these faunas contain an abundant cephalopod assemblage, mostly small, which are associated with other dwarfed and nondwarfed invertebrates. The problems involved with dwarfed cephalopods and their environment are principally recognition of a mature cephalopod and to explain why dwarfism itself appears to be selective as to genera and species within the faunal assemblage. Relatively simple environment causes for dwarfism as proposed by Shimer and others are insufficient to explain the faunas under study.

MOLLUSCA (EXCLUSIVE OF AMMONOIDA)

H. B. Stenzel, University of Texas, Austin.

As a first step in the elucidation of dwarfed faunas the significance of faunas having small average stature is discussed. The average size of individuals of a genus as a rule increases in successive stratigraphic horizons. This is demonstrated on the phylogenetic history of the molluscan genera Distorsio, Strombus, Turricula, and others. Hence older Tertiary molluscan faunas have small average stature in comparison with younger Tertiary and living faunas, hence resemble dwarf faunas. This size increase is genetic. As a second step attention is called to recent studies on transplanted infertile American oysters in England. In these studies the influence of location on size is demonstrated. These size differences are entirely environmental, because all oysters came from the same genetic stock. Attention is also called to the influence of brackish-water environment on average age of populations and shell size.

CRUSTACEA

Harold W. Scott, University of Illinois, Urbana.

A survey of literature on fossil and living crustacea fails to uncover a single reported case of unquestioned dwarfing.

The molt stages of crustacea introduce a factor that is not ordinarily involved in the study of other invertebrates. Ostracodes pass through seven to nine molt stages. It is conceivable that a group of molts could be misinterpreted as dwarfing. Though ostracodes live in a great variety of environments, ranging from marine to all moist terrestial habitats in most latitudes, none is known to be dwarfed. Ostracodes range from the Ordovician to Recent, but there is no known fossil fauna that can be remotely construed as being dwarfed.

An investigation concerning dwarfing in trilobite faunas is in progress, but no evidence has been thus far discovered which would indicate the existence of such a fauna.

Latitude does not cause the dwarfing of modern crustaceans. Size of streams or lakes, or position in the stream does not cause a reduction in size. Ortman's law, as applied to pelecyopods and gastropods, cannot be applied to crustaceans.

Abstracts of other papers of particular interest to ecologists are the following:

THE IMPORTANCE OF CORALLINE ALGAE IN REEF BUILDING AT BIKINI, MARSHALL ISLANDS

J. Harlan Johnson, U. S. Geological Survey.

At Bikini coralline algae are of primary importance as reef builders. The reef was carefully studied at a number of localities. The relative importance of the algae varied with locality, the content ranging from 55 to 90 percent. The number of species present was surprisingly small, but the number of individuals was enormous. The algae not only contribute much of the volume of material but also form the stong compact outer margin of the reef (the Lithothamnion ridge) which protects it from wave erosion; they cover and bind corals and other organisms, together giving the reef coherence.

THE FORAMINIFER ORBULINA UNIVERSA D'ORBIGNY AS A POSSIBLE MIDDLE TERTIARY TIME INDICATOR

L. W. Le Roy, Colorado School of Mines, Golden.

It is suggested that points of lowest biostratigraphic occurrence of the pelagic foraminifer Orbulina universa d'Orbigny occurring in a continuously deposited, open-sea, deep-water globigerine-facies sequence, fall on or in close proximity to a time horizon within Middle Teritary sections now situated in tropical and subtropical zones of the world. It is recommended that these points constitute a datum to be termed the "Orbulina surface." The definition of this surface would assist materially in establishing world-wide Tertiary time-stratigraphic correlations. The distribution and significance of Orbulina and its allied form, Candorbulina, in the Kassikan section of central Sumatra are discussed. This section is believed to contain a qualified point for the "Orbulina surface" and is recommended as the type for the western portion of the East Indian Archipelago.

PRINCIPLES OF REGIONAL SEDIMENTARY STRATIGRAPHIC ANALYSIS

W. C. Krumbein, Northwestern University, Evanston, Illinois.

Lithofacies maps may be prepared in a number of ways, and the present paper emphasizes a statistical approach which brings out rates of change, to indicate whether facies transitions are rapid or slow. The method consists in using a "clastic ratio" based upon the ratio of sand plus shale to limestone plus evaporites. This is supplemented by a "sand ratio," which is the ratio of sand to shale in the section, regardless of the nonclastics. The data obtained are numerical and provide a basis for contour-type maps of statistical lithologies. For the more detailed analysis of lithofacies, a series of ratios based on sandstone and limestone types is available, which helps distinguish platform, basin, and geosynclinal deposits. The use of general or specific lithofacies

ratios in conjunction with isopach maps affords data for interpretations of contemporary tectonics, paleogeography, and to some degree the distribution of environments during the depositional cycle.

ASSOCIATIONS OF LITHOLOGIC AND TECTONIC ENVIRONMENTS IN THE CENTRAL STATES

E. C. Dapples, W. C. Krumbein, and L. L. Sloss, Northwestern University, Evanston, Illinois.

Lithologic responses to tectonic controls permit the organization of sediments into several broad groups, depending upon their accumulation on platforms, in basins, or in geosynclines. Each lithologic association includes particular sandstones, shales, and limestones, which in the aggregate are the result of the tectonic framework, the tectonic intensity, and the nature of the depositional environment. This paper attempts to integrate these three points of view, each of which bears on the problem of interpreting the ancient rock column. Examples illustrated by regional maps showing broad variations and changing lithologic associations for selected geologic intervals are given, and integrated into a tabular summary of associated rock types, broad environmental patterns, and tectonic framework.

Anne and Prof. T. A. Stephenson have published (privately printed) a brief report on their studies of intertidal environments in North America carried out during 1947-48. This work was part of a world wide survey.

James Steele Williams and V. E. McKelvey report as follows on current studies of the Phosphoria formation:

"Studies of the ecology of the invertebrates of the Phosphoria formation (Permian) are being made in connection with paleontologic and related studies by James Steele Williams and associates and with stratigraphic, sedimentation, economic, and other investigations under the direction of V. E. McKelvey. These studies, which continue those previously made by earlier paleontologists and geologists of the Federal Geological Survey, began several years ago and probably will continue for some time. Detailed stratigraphic sections are being made from both surface outcrops and trenches. Most of these sections are in areas that have been or are being mapped geologically. Geological Survey parties at several places in Idaho, Montana, Wyoming, Utah, and Colorado are cooperating.

"Collections of fossils are being carefully made from each thin lithologic zone recognized in each stratigraphic section. A specially devised schedule is followed for describing each collection. This schedule includes such data as the following: lithology of the unit from which collected; percentage of the rock composed of fossils; recognizable phyla and classes and approximate percentage of each; recognizable genera and species and approximate percentage of each type; mineral composition, and conditions of preservation; evidence of reworking; sizes of fossils or fragments; distribution within bed or zone and relation to different lithologic types of the zone; orientation of specimens; special modes of occurrence; and other miscellaneous data. The results of extensive sedimentation studies, for which field data comparable to the above are being collected by McKelvey and associates, will later be available for coordination with the records of the fossils.

"Units of the studies are being published separately. It is hoped to later combine into several large volumes data from these separate units augmented with overall interpretations."

OUTSIDE THE UNITED STATES

Work on a final report covering studies of the submarine geology and reefs of Bikini Atoll in the Marshall Islands was continued by K. O. Emery, J. I. Tracey, Jr., and H. S. Ladd of the U. S. Geological Survey, and Gordon Lill of the Office of Naval Research. Arrangements are being made with the British Museum to borrow the core obtained on Funafuti in the Ellice Island so that comparative studies may be made. Special reports on certain organic groups (both Recent and fossil forms) are being prepared as follows: Algae by J. Harlan Johnson, Smaller Foraminifera by J. A. Cushman, Larger Foraminifera by W. Storrs Cole, Corals by J. W. Wells, of the Geological Survey. Dr. Wells has identified a larger number of Recent corals from Bikini than have been reported from any other locality in the Pacific area. Since Bikini lies far from the centers of coral dispersal in the East Indies, this number reflects the intensity of collecting.

Prof. Robert W. Hiatt of the University of Hawaii is completing his Bikini ecological report on food-chains and the food cycle of reef invertebrates and fish.

The American Museum of Natural History has established a permanent marine laboratory on the British island of Bimini in the Bahamas, about 50 miles east of Miami, Florida. The station is to be known as the Lerner Marine Laboratory.

Louis W. Hutchins of the Woods Hole Oceanographic Institution reports as follows on plans to explore the Atlantic Ridge during the summer of 1948:

"Under the joint sponsorship of the National Geographic Society, Columbia University, and the Woods Hole Oceanographic Institution, the latter's research ketch ATLANTIS will make further explorations of the Mid-Atlantic Ridge during the summer of 1948. The work, directed by Dr. Maurice Ewing, will be a continuation of the geological, geophysical, and biological investigations begun last year.

"The program includes mapping of the topography of the Ridge, coring and other studies of the sediments, investigation of the bottom by means of underwater photography, dredging for rocks, and trawling and dredging for biological specimens. It is hoped that several seamounts can be located and explored in some detail, since available evidence suggests that knowledge of the structure and fauna of these features will throw considerable light on the general history of the Ridge."

According to a report in Pacific Science, plans for the erection of the building for the Hawaii Marine Laboratory were completed early in 1948. The laboratory will be situated on the island of Moku-O-Loe in Kaneohe Bay, Oahu, and the University of California will cooperate with the University of Hawaii in its operation. The report states further:

"Plans outlined for oceanographic research at the laboratory emphasize those aspects of oceanography peculiar to this sub-tropical region

of the central Pacific. Broadly speaking, the oceanographic program may be called a study of the ecology of the near-shore and off-shore waters around the islands of Hawaii, and the study is readily divided into three phases: (1) Ecology of the near-shore waters, i.e., primarily the waters inside the reefs; (2) ecology of the transition region beyond the reef; (3) ecology of the oceanic waters.....

"It is believed that for some time the oceanic work will be strictly exploratory. Routine observations, including temperature, salinity, minor constituents, transparency, and biological features, will be made of the character of the surface layer and of the waters at or directly below the thermocline."

The U. S. Navy Hydrographic Office, in cooperation with the Office of Naval Research, continued to investigate the oceanography of Arctic waters whenever opportunity permitted. Mr. Gerald Metcalf of the Woods Hole Oceanographic Institution and Mr. Jacob Wickham of the Scripps Institution of Oceanography were assigned as naval technicians during the summer of 1948. Considerable information was obtained on thermal structure, ice conditions, and bottom sediments during the cruise through Arctic waters. Similar information was obtained during the Point Barrow Resupply Expedition (1948) by Mr. Warren Wooster, Scripps Institution of Oceanography, who was also made a naval technician for the summer.

The U. S. Geological Survey, in cooperation with the Corps of Engineers, U. S. Army, is continuing its program of geologic mapping in the Pacific Islands, under the direction of S. K. Neuschel. Field work on Yap has been completed, and the report is being prepared by Charles G. Johnson. Studies are now under way on Okinawa, directed by Delos E. Flint; on Palau, under Arnold C. Mason; and on Saipan and Guam, under Preston E. Cloud, Jr. Collections of fossil and Recent faunas are being made, from which it is expected that considerable paleoecologic data will result.

The fossil mollusks of Okinawa are now being studied by F. Stearns MacNeil, and the larger Foraminifera of Saipan by W. Storrs Cole.

RECENTLY PUBLISHED PAPERS

Most of the papers listed below appeared during the year ending May 1, 1948.

GENERAL

Allan, R. S.
Geological correlation and paleoecology: Geol. Soc. America Bull., vol. 59, no. 1, pp. 1-10, 1948.

Bassindale, R.
The invertebrate fauna of the southern shore of the Bristol Channel and Severn Estuary: Bristol Naturalists Soc. Proc., 4th Ser., vol. 19, pt. 2, pp. 143-201, 1941.

Caster, Kenneth E.
(and Petril, Setembrino). Devonian stratigraphy and paleontology of the States of Parana and Sao Paulo, Brazil, (Abst.): Geol. Soc. America Bull., vol. 58, no. 12, (Pt. 2), p. 1173, 1947.

Chatwin, C. P.
British Regional Geol., East Anglia and adjoining areas, (2d. edition): Dept. Sci. and Industrial Research, Geol. Surv. and Mus., pp. 1-97, 1948.

Daly, Reginald A.
Coral Reefs--A Review: Am. Jour. Sci., vol. 246, no. 4, pp. 193-207, 1948.

Dapples, E. C.
Sandstone types and their associated depositional environments: Jour. Sed. Petrology, vol. 17, no. 3, pp. 91-100, 1947.

Dewey, Henry
British Regional Geology, Southwest England (2d. edition): Dept. Sci. and Indust. Research, Geol. Survey and Mus., pp. 1-67, 1948.

Edmunds, F. H.
British Regional Geology, Wealden Dist. (2d. edition): Dept. Sci. and Indust. Research, Geol. Surv. and Mus., pp. 1-93, 1948.

Emery, K. O.
Ranger Bank, Mexico, (Abst.): Geol. Soc. America Bull., vol. 58, no. 12, (pt. 2), p. 1177, 1947.

Evans, R. G.
1. The intertidal ecology of Cardigan Bay: Jour. Ecology, vol. 34, no. 2, pp. 273-309, 1947.
2. The intertidal ecology of selected localities in the Plymouth neighbourhood: Jour. Marine Biol. Assoc. United Kingdom, vol. 27, no. 1, pp. 173-218, 14 fig., 1947.

Filatova, Z. A.
A quantitative evaluation of the bottom fauna of the southwestern part of the Barents Sea: Repts. Polar Res. Inst. Sea Fish. and Oceanogr. Murmansk. 2 (1): 3-58, 3 maps, 6 fig., 1938 (In Russian).

The work based on 196 bottom samples taken with several kinds of collectors. The biomass of the fauna varied from 2 or 3 g. to several kg. per sq. meter. Richest faunas occur near shore and at the edges of banks. The faunas were divided into 12 complexes or communities, characterized by dominant, secondary or unimportant species. The zoogeographical relationship of these complexes was described. A boundary between "Boreal" and "Arctic" faunas was established. (Gordon Gunter).

Gislén, Torsten
Conquering terra firma. The transition from water to land-life: Kungl. Fysiografiska Sällskapets I Lund Förhandlingar, Bd. 17, Nr. 21, pp. 1-20, 1947.

A general description of the problems of migration from sea to land. The author concludes that most terrestrial animals originally invaded land from brackish or fresh-water coasts. (J. W. Hedgpeth).

Gill, Edmund D.
The study of eustatic changes of sea-level: Australian Jour. Sci., vol. 10, no. 3, pp. 63-67, Dec. 1947.

Gunter, Gordon
1. Differential rate of death for large and small fishes caused by hard cold waves: Science, vol. 106, p. 472, Nov. 14, 1947.
2. Extended remarks on relationships of marine animals to salinity: Jour. Paleontology, vol. 21, no. 5, pp. 498-500, 1947.
3. Catastrophism in the sea and its paleontological significance, with special reference to the Gulf of Mexico: Am. Jour. Sci., vol. 245, no. 11, pp. 669-676, 1947.

Hardy, A. C.
(and Paton, W. N.). Experiments on the vertical migration of plankton animals: Jour. Marine Biol. Assoc., vol. 26, no. 4, pp. 467-526, 1947.

Harvey, H. W.
Manganese and the growth of phytoplankton: Jour. Marine Biol. Assoc., vol. 26, no. 4, pp. 462-579, 1947.

Hedgpeth, Joel W.
The Laguna Madre of Texas: N. Am. Wildlife Conf. Trans., vol. 12: 364-380, 6 figs., 1948.

The Laguna Madre is in last stages of its geological history, without river supply or adequate openings to the Gulf. The patterns of surface salinity indicate the behavior of highly saline waters in a restricted bay. Every few years salinity exchange breaks down through a combination of low rainfall, high summer temperatures and low tides and catastrophic mass mortality to fish occurs.

Hutchins, Louis W.
The bases for temperature zonation in geographical distribution: Ecol. Mon., vol. 17, pp. 325-335, 1947.

Krumbein, W. C.
Shales and their environmental significance: Jour.Sed. Petrology, vol. 17, no. 3, pp. 101-108, 1947.

Ladd, H. S.
(and Tracey, J. I., Lill, Gordon, Wells, J. W., and Cole, W. S.). Drilling on Bikini Atoll, Marshall Islands, (Abst.): Geol. Soc. Amer. Bull., vol. 58, no. 12, (pt. 2), pp. 1201-1202, 1947.

Lowenstam, Heinz
Biostratigraphic study of the Niagaran inter-reef formation in northeastern Illinois: Ill. State Mus. Sci. Papers, vol. 4, pp. 1-146, pls. 1-7, Jan. 1948.

This is a noteworthy pioneering effort to relate paleontology, stratigraphy and paleoecology in the study of facies faunas. It is especially interesting inasmuch as he demonstrates that faunas previously considered to be provincial are actually facies faunas. The work on which the paper is based was undertaken to show that so-called southern faunal elements, supposed to represent a geographically isolated fauna of Niagaran time in western Tennessee, occur in all of the inter-reef facies of the abundant Niagaran coral reefs of northeastern Illinois. The work also shows that the so-called northern faunal element is the rough water reef facies fauna. The conclusions in this paper concerning provincial faunas of the Niagaran should lead to reconsideration of other so-called provincial faunal problems.

A great wealth of paleoecological data and interpretations are presented. Many of the data are loosely tied into the problem of provincial faunas. However, this report has a two-fold scope, i.e., the discussion of the faunal elements and the description of significant faunal assemblages as related to ecological environments of the Niagaran rocks concerned in this report. The paleoecological data are to serve as reference material for Lowenstam in several forthcoming stratigraphic and paleontologic studies of these strata.

A significant omission is the failure clearly to outline the stratigraphy for those unfamiliar with the Niagaran rocks of northeastern Illinois and failure to clarify the inter-relation of facies and their faunas to the stratigraphic framework of the region. These omissions possibly were caused by the special scope of the investigation.

Finally this report is an important contribution to paleontology because it presents evidence that we must reconsider provincial faunal problems in the light of paleoecological relations. It thus represents a valuable source book of Niagaran paleoecological data. (Arthur L. Bowsher)

Lowman, S. W.
Project 5 - Recent and near-Recent sediments of the northern Gulf of Mexico-Gulf Coast Region: Repts. on Projects, Amer. Assoc. Petrol. Geol. Research Comm. 1946-47, pp. 52-97, 1947.

Moore, Raymond C.
Stratigraphical Paleontology: Geol. Soc. Amer. Bull., vol. 59, pp. 301-326, 1948.

Mullerried, F. K. G.
Paleobiologia de la caliza de Cordoba y Orizaba, Ver.: Anales del Inst. de Biologia, vol. 18, no. 2, pp. 361-462, 1947.

Pettersson, Hans
Iron and manganese on the ocean floor: Kungl. Vetenskaps-och Vetterhets-Samhalles, Handlingar, Sjatte Foljden, Ser. B, Bd. 3, no. 8, pp. 1-37, 1945.

Pora, E.
1. (and Carausu S.). Sur la résistance de l'amphypode Pontogammarus maeoticus (Sow.) Mart. De la mer noire, aux variations de salinité du milieu ambiant: Annales Scientifiques de l'Université de Jassy., vol. 25, Fasc. 1, pp. 1-14, 1939.
2. Sur l'adaptation d'un teléostéen dulcaquicole, Carassius carassius L., au milieu salin: Bull. de la Societe des Sciences de Cluj (Roumanie), vol. 9, pp. 384-393, 1939.
3. Problèmes de Physiologie animale dans la Mer Noire: Bull. de l'Institut Océanographique, no. 903, pp. 1-43, 1946.

Discusses the distribution of marine organisms in relation to salinity gradients in the Black Sea and tidal waters of Roumania. (J. W. Hedgpeth)

4. (and Rosca, D. I.). La Survie du vers polichaete nereis diversicolor de la mer noire et du lac salé d'eforia, dans des milieux de salinités différentes: Annales Scientifiques de L'Université de Jassy., vol. 30, Fasc. 1-2, pp. 1-17, 1947.

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(and George, T. Neville). British Regional Geology, South Wales, (2d. edition): Dept. Sci. and Indust. Res., Geol. Survey and Mus., pp. 1-100, 1948.

Prouty, C. E.
Relationship of Cambro-Ordovician dolomites to facies barriers in Tennessee and Virginia, (Abst.): Geol. Soc. Amer. Bull., vol. 58, no. 12, (pt. 2), pp. 1218-1219, 1947.

Purchon, R. Denison
An ecological study of the beach and the dock at Portishead: Bristol Naturalists' Society Proc., 4th Ser., vol. VIII, pt. III, pp. 311-329, 1938.

Richardson, J. A.
Facies change and lithological variation in the Permocarboniferous formation of North-West Pahang and South-West Kelantan, Malaya: Geol. Mag., vol. 84, no. 5, pp. 281-288, 1947.

Shepard, Francis P.
1. Diving operations in California submarine canyons, (Abst.): Geol. Soc. Amer. Bull., vol. 58, no. 12, (pt. 2), p. 1227, 1947.
2. Hawaiian submarine canyons, (Abst.): Geol. Soc. Amer. Bull., vol. 58, no. 12, (pt. 2), p. 1227, 1947.

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Note on paleoecological import of salinity: Jour. Paleontology, vol. 21, no. 3, pp. 294-295, 1947.

Sloss, Laurence L.
Environments of limestone deposition: Jour. Sed. Petrology, vol. 17, no. 3, pp. 109-113, 1947.

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(and George, T. Neville). British Regional Geology, North Wales, (2d. edition): Dept. Sci. and Indust. Res., Geol. Surv. and Mus., pp. 1-89, 1948.

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The colors of marine animals: Endeavour, vol. VI, no. 24, pp. 152-159, 1947.

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(and Fairbridge, R. W.). Some coral reefs of the Sahol Shelf: Geog. Review, vol. 38, pp. 222-249, April 1948.

Trask, Parker D.
1. (and Phleger, Fred B., Jr. and Stetson, Henry C.). Recent changes in sedimentation in the Gulf of Mexico: Science, vol. 106, pp. 460-461, Nov. 14, 1947.
2. (and Stetson, Henry C., and Phleger, Fred B., Jr.). Sub-arctic sediments in the Gulf of Mexico, (Abst.): Geol. Soc. Amer. Bull., vol. 58, no. 12, (pt. 2), pp. 1233-34, 1947.

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The seasonal occurrence of sedentary marine organisms in Biscayne Bay, Florida: Ecology, vol. 29, no. 2, pp. 153-173, 1948.

Wells, John W.
Provisional Paleoecological Analysis of the Devonian rocks of the Columbus region: Ohio Jour. Sci., vol. 47, pp. 119-126, 1947.

Wheeler, H. E.
(and Beesley, E. Maurice). Critique of the time-stratigraphic concept: Geol. Soc. Amer. Bull., vol. 59, no. 1, pp. 75-86, 1948.

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The Geology of Nashville, Tenn.: Tennessee Div. Geol., Dept. Conservation, Bull. 53, pp. 1-172, 1948.

PLANTS

Brill, Kenneth G., Jr.
Cryptozoon sp., an Ordovician algae from southeastern Tennessee, (Abst.): Geol. Soc. Amer. Bull., vol. 58, no. 12, (pt. 2), pp. 1168-69, 1947.

Cottam, Clarence
(and Addy, C. E.). Present eelgrass conditions and problems on the Atlantic coast of North America: N. Amer. Wildlife Conf. Trans., vol. 12: 387-398, 1948.

The status of eelgrass in 1946 was favorable, indicating a gradual return of this plant to the tidal areas after the epidemics of 1931-32. (Gordon Gunter).

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The occurrence of Hydrodictyon reticulatum (L.) Lagerh. in brackish waters in Belgium: Ecology, vol. 28 (3): 317-319, 1947.

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(and Blomquist, H. L.). A Collection of Marine Algae from Brazil: Torrey Bot. Club Bull., vol. 74, no. 5, pp. 383-397, 1947.

PROTOZOANS

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Fossil Tintinnids: loricated Infusoria of the order of the Oligotricha: Jour. Paleontology, vol. 22, no. 2, pp. 233-263, 1948.

Crespin, Irene
Foraminifera in the Permian rocks of Australia: Bur. Mineral Res., Geol. and Geophysics Bull. 15, pp. 1-31, 1947.

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(and Renz, H. H.) The foraminiferal fauna of the Oligocene Ste. Croix formation of Trinidad, B.W.I.: Cushman Lab. for Foraminiferal Research, Spl. Pub. no. 22, pp. 1-46, 1947.

Parker, Frances L.
Foraminifera of the continental shelf from the Gulf of Maine to Maryland: Mus. Comp. Zool. Bull., vol. 100, no. 2, pp. 211-253, 1948.

Phleger, Fred B., Jr.
Methods of study of Recent Foraminifera (Abst.): Geol. Soc. Amer. Bull., vol. 58, no. 12, (pt. 2), p. 1218, 1947.

Rau, Weldon W.
Foraminifera from the Porter shale (Lincoln formation), Grays Harbor County, Washington: Jour. Paleontology, vol. 22, no. 2, pp. 152-174, 1948.

Todd, Margaret Ruth
Vicksburg Oligocene Foraminifera from Mississippi, (Abst.): Geol. Soc. Amer. Bull., vol. 58, no. 12, (pt. 2), p. 1233, 1947.

Van Overbeck, J.
(and Crist, Raymond E.). The role of a tropical green alga in beach sand formation: Am. Jour. Botany, vol. 34, no. 6, pp. 299-300, 1947.

SPONGES

de Laubenfels, M. W.
Ecology of the sponges of a brackish water environment at Beaufort, N. C.: Ecol. Monographs, vol. 17, no. 1, pp. 31-46, 1947.

COELENTERATES

Crossland, C.
Reef corals of the South African Coast (with addenda by T. A. Stephenson): Ann. Natal Museum, vol. 11, pp. 169-205, 1948.

Contains important ecological notes on this very southerly coral fauna and comparisons with other faunas in the Indo-Pacific. (John W. Wells).

Dons, C.
Norges korallrev [The coral reefs of Norway.]: K. Norske Vidensk. Selskab. Forhandl. [Trondhjem] 16A: 37-82, 15 fig., 1943.

Along the Norwegian coast are about 65 recent reefs and about 35 subfossil ones, 8 above sea level. The northernmost reef is at 70° 57' N. lat. The madreporian, Lophelia pertusa, forms the main part of every reef. Depths, distributions, and lists of animals found regularly and exclusively on the reefs are given. (Gordon Gunter).

Hill, Dorothy
The Distribution and Sequence of Carboniferous Coral Faunas: Geol. Mag., vol. LXXXV, no. 3, pp. 121-148, 1948.

Richards, Horace G.
Preservation of fossil jellyfish, (Abst.): Geol. Soc. Amer. Bull., vol. 58, no. 12, (pt. 2), p. 1221, 1947.

Umbgrove, J.H.F.
Coral Reefs of the East Indies: Geol. Soc. Amer. Bull., vol. 58, no. 8, pp. 729-778, 1947.

BRYOZOA

Marcus, E.
Bryozoarios perfuradores de conchas (Shell burrowing polyzoa): Arquivos do Instituto Biologico, vol. 9, Art. 25, pp. 273-296, 1938.

Describes zoocia of Boring Bryozoa of the family Terebriporida. The position in the stoloniferous Ctenostomata is confirmed. (J. W. Hedgpeth).

BRACHIOPODA

Cloud, Preston E., Jr.
Notes on Recent Brachiopods: Am. Jour. Sci., vol. 246, no. 4, pp. 241-250, 1948.

Elliott, Graham F.
Distribution des Brachiopodes en espèces et ses causes, illustrée par les Térébratulinides de l'Eocene de l'Europe occidentale: Soc. Géol. France, Bull., 5th Sér., vol. 17, fasc. 1-3, pp. 67-80, January 1947.

The widespread changes in the distribution of land and sea that marked the close of the Cretaceous, together with resultant modifications in ecology and climate, placed a serious challenge on these organisms adapted to the tranquil conditions of the late Mesozoic. A form perfectly adapted to a given environment is no longer in harmony when that environment changes and the qualities requisite for the colonization of a new area differ from those necessary to maintain an old. With this in mind, it is interesting to examine the living forms that persist from one period to another but are not equally common in both. All the textbooks stress the relative rarity of the brachiopods in the Tertiary rocks in marked contrast to their abundance and their value as time markers in the Cretaceous. However, the change

both in the hard and soft parts between the brachiopods of the Senonian and the Tertiary and living species is not conspicuous.

The position held by the brachiopods in the Cretaceous marine communities is occupied largely in the Tertiary and Recent seas, by the pelecypods. Most of the pelecypods have the advantage of being able to move from place to place while, on the other hand, the brachiopods are fixed by their peduncles. Even the larvae are at a disadvantage for, in comparison with the bivalves, the free-swimming stage is very short. According to Schuchert, 1911, 71 percent of the living species are found between low-tide level and 180 m. The inarticulate Lingulas and Discinides include a minority confined strictly to warm shallow waters and muddy bottoms. The articulates, however, which are in the majority, frequent the rather deep waters, far on the outer margin of the continental shelf from the sublittoral and neritic zones teeming with molluscan life. Among the articulates listed by Thomson, 1927, 28 percent live above the 180-m. line, 34 percent may pass it and 38 percent live below it.

It would be interesting to know the Cretaceous-Eocene history of that part of Japan, which possesses the richest brachiopod fauna in the world. Outside of Europe, the scattering of the brachiopods seems to have been determined by the breaking up of the old Mesozoic continent to the south of Tethys. The terebratulinids of the Eocene of western Europe have prospered only in rather deep water and not in the more shallow water to which they are physically adapted and which they were occupying at the close of the Cretaceous.

The decline of the brachiopods in the Tertiary is explained not by any modification in their structure or by any degeneracy but by their constitutional inaptitude to struggle victoriously with the Mollusca under changing conditions.

The bibliography at the close included 40 citations. (Julia Gardner).

MOLLUSKS

Baughman, J. L.
An annotated bibliography of oysters with pertinent material on mussels and other shellfish and an appendix on pollution: Texas A. and M. Research Foundation, pp. 1-794, 1948.

Burch, Beatrice L.
Comparison of the mollusks of three Pleistocene beds with the Recent fauna of Los Angeles County, Calif.: Minutes Conchological Club of Southern Calif., No. 73, pp. 1-18, Sept. 1947.

Carcelles, Alberto
1. Notas sobre algunos Gastropodos marinos del Uruguay y La Argentina, I-VI: Comunicaciones Zoologicas del Museo de Historia Natural de Montevideo, No. 40, Vol. II, pp. 1-27, 6 figs., 7 pls., 1947.
2. Notas sobre algunos bivalvos argentinos: Comunicaciones Zoologicas del Museo de Historia Natural de Montevideo, No. 41, Vol. II, pp. 1-10, 3 figs., 1 pl., 1947.

Chavan, A.

L'Evolution des Faunes Marines de Mollusques dans le Nord-Ouest de l'Europe, de la Fin du Cretace a celle de l'Eocene: Geol. Soc. France Bull., 5th Ser., vol. 16, fasc. 4, 5, 6, pp. 193-212, 1946.

The Lower Tertiary Mollusca of western Europe are known from 3 areas; a northern which includes Denmark and Holland; a southern, best represented in Aquitaine and the Corbieres, and the intermediate Anglo-French-Belgian basin. The different stages recorded have been analysed both stratigraphically and paleontologically and the mollusks, which make up the greater part of the faunas, have been considered in greatest detail. An attempt has been made to establish the geographic and climatic significance of each genus.

I. Campanienne

In order to arrive at accurate conclusions, we must know the foundation fauna from which the lower Tertiary species were derived, and we must go back to the last period of open Cretaceous sedimentation undisturbed by appreciable introductions from other areas. The Campanienne serves as such a control. An important marine transgression took place toward the end and, in the Maestrichtien, several decidedly southern types such as the orbitoids had already arrived in Holland by way of the Atlantic and the Manche. The best known fauna in the Campanien of the Paris Basin is meager and was probably laid down under more than 350' of water. The molluscan genera are much the same as those in the older chalk beds. Most of them, such as Spondylus, Chlamys, Pycnodonta, Dentalium s. l. and Turritella, belong to stable types which made their first appearance long ago and are, for the most part, still living. With them are associated some typically Cretaceous genera such as Gyropleura, Inoceramus, Neithea and Belemnitella.

In the topmost Campanien, however, where the chalk becomes hard, as at Meudon, are the remains of a neritic fauna of somewhat dubious affinities. A probably synchronous and much richer fauna is recorded in the Hervien glauconitic sands of Vaals near Aix-la-Chapelle on the German-Holland boundary. Holzapfel, who has made the most exhaustive study of the fauna, recognized 126 genera of mollusca, 83 of them with living representatives. One hundred and fifty-three genera have been listed by later students; 58% to 69% of these are still living but they are closely related to old and stable types. A number of the genera recorded at Vaals are present also in the Cretaceous of North America and indicate a communication between these two great northern provinces near the close of the Cretaceous. Among these are Trinacria, Cucullaea, Latiarca, Crenella, Exogyra, Vetercardia, Isocardia, Cyprimeria, Liopistha, Cuspidaria, Emarginula, Tudicla, Scaphites, Baculites, etc. The fauna indicates a temperate sea and seems, for the most part, to have developed in situ.

II. Maestrichtien

In northwestern Europe, the transgression of the Maestrichtien in the Pays-Bas is recorded in the tuffeau of Montagne-Saint-Pierre; its fauna is characterized by the intermingling of the large warm water Formainifera, the orbitoids, and by the abundance of the gastropod Otostoma. In the Paris Basin, no trace remains of a synchronous fauna and an emergence or at least a hiatus in marine sedimentation is generally conceded.

In the Cotentin, the yellow limestone containing Baculites is reported by a number of students but the gastropod and pelecypod faunas are no better known than those from the hard chalk of Meudon. In the Pays-Bas, most of the genera making their first entrance, seem to be derived from native faunas, and apart from the invasion of the orbitoids, there is no certain evidence of a southern migration into the northwestern sea.

III. Danien

Like many contact formations, correlation of the Danien has been highly controversial. Its individuality has been questioned because it represents lithologically and zoologically one or the other of the formations which it separates. But it is now established that a general regression terminated the Maestrichtien, not only in Denmark but throughout the north European basin. There is a hiatus in sedimentation, longer in some countries such as southern England, shorter in Denmark and Scandinavia where the Danien overlies Maestrichtien beds but differs from them in the absence of all Ammonites and Belemnitella. In the faunal analysis, only the assemblage from the type locality at Faxe is considered. Ravn, who studied it most carefully, included in it, 69 certain genera and 30 others represented by atypical species. Nucula, Gastrochaena and Phaladomya determined by Hennig from the nearby Annetorp beds have been added. Thirty of the 102 genera under observation are apparently extinct. Several genera such as Arcopsis, Collonia, Bittium, Cerithiopsis, Aclis and Fusimitra may be indiginous; Surcula seems to be of American origin; Sassia has been recorded in the Maestrichtien; but Acrilla, Cavoscala, Vicetia, Eocypraea and Lyria were living in the Tethyan sea before Danien time, and forms the first important group of southern migrants.

IV. Montien

In the Montien, transgressive both on the Danien and the Cretaceous, two faunas may be recognized, one from the limestone at Mons in Belgium, the type locality, the other--the Vestre Gasvoerk fauna--from the clays and green sands of Copenhagen. The sea in which the rich Montien fauna lived as probably open to the Tethyan sea on the west; the Danish assemblage probably lived in a sea open to the east into Russia and there is no evidence of direct communication between the two basins. A new era opens with the Montien. The great reptiles and the ammonites disappear, the Brachiopods decline and the mammals begin to burgeon.

The Montien mollusca which include 240 species differs from the Danien in the following characters:

1. Characteristic Cretaceous genera are no longer present.
2. Of the old foundation fauna, only the stable types survive and these are relatively few in comparison with those of infra-Cretaceous origin (Glycymeris, Crassatella) and especially with the upper Cretaceous arrivals, such as Chama, Tuba, Mathilda, Eulima, Pseudoliva and Ringicula.
3. The restricted genera are not the same as those at Faxe.
4. A series of unquestioned migrations are evident, most of them from the warmer seas. Venericardia (Venericor), Eomiltha, Tuba, Mesalia (Sigmesalia) Clava s.l., Semivertagus, Ptychocerithium, Batillaria, Pyrazus, Sigaretopsis, Cominella, and Acteon and possibly Glans, Paraglans, Cepatia and Cryptoconus are counted among the migrants. In the Paris Basin, Mesalia is particularly characteristic of this warm water invasion.

Among the immigrants from North America are Parvilucina, Scintilla, Gobraeus, Tympanotonus, Calyptraphorus, Ancilla s.l. and Olivella.

5. The Montien marks the first appearance of Cavilinga, Microloripes, and Corbulomya. Other forms, some indigenous, others possibly invaders, include

Cardita and Miltha, possibly of American origin, Sportella, Erycina, Peronidia, Adeorbis, Cyclostrema, Benoistia, Teliostoma, Muricopsis, Priscoficus, Vereonella, Mitreola, Cryptochorda, Clinura and Beloptera.

The fauna of Copenhagen is another expression of the Montien, but more northern and without direct communication with the Belgian deposits. A number of cool water genera such as Astarte, Lacuna, Aporrhais, Exilia and Admete are to be found at Copenhagen but not at Mons. On the other hand, the warm water Montien genera such as Cepatia, Sigaretopsis, many of the turrids and Acteon are absent at Copenhagen. A number of indigenous first appearances have been recorded at Copenhagen; and migrants, such as Cassidaria, Clavilithes, and Genota, from relatively warm water and from the temperate seas, Properamussium, Eocantharus, Verticordia and Suessonia.

V. Thanet

The analysis of the Thanetian fauna is important not because of the individuality of the assemblage but because of its bearing on the temperature of the Thanetian sea which opened northward and covered southern England, Limbourg, Belgium, and the southern part of the Paris Basin. Aporrhais and Cyprina together with Nuculana, Thyasira, Panope, Lyonsia, Thracia, Saxicava, Lacuna, Acirsa and Bela characterize the Paris Basin fauna. In England, this same fauna is augmented by Astarte, the cachet of cool water. The coexistence of the cool temperate forms with typical tropical genera such as Eucrassatella, Priscoficus, Scaphella, Athleta, Conomitra, Sassia, etc., has been explained by appropriate currents. Other genera such as Mesalia, Ancilla and Olivella, which were present in the Montien at Copenhagen, did not reappear until the Cuisien. Apparently, in the Thanet, the immigrations from the south ceased or slowed down; the communication toward the northeast was reestablished while the western invasion route was closed or lengthened. The warm water forms which remained were limited in number and adjusted to changes in environment. The Thanetian climate was not tropical but only Mediterranean, probably with warm and cool currents, for the Bracheux fauna seems to be cooler than that around Rheims. The rather numerous calcareous algae of the Thanetian also favor a Mediterranean climate.

VI. Cuisien

The Cuisien is marked by the reestablishment through the northwest passage across the Manche of communications with the Tethyan sea. This conclusion is supported by the following facts:

1. The return of subtropical genera banished from the Thanet seas; such as Mesalia introduced into the Paris Basin and Clavilithes, Suessonia and Sparella into the Montien of Denmark.

2. The final disappearance of certain cool water genera such as Lyonsia, which probably evolved in situ and migrants from the North such as Astarte, Cyprina, Aporrhais and Dosiniopsis.

3. Migrants from the south such as Vulsella, Lucina s.s., Pterolucina, Nicorbula, Niso, Rimella, Cyclomolops, Gisortia, Terebellum and Strepsidura.

4. Other newcomers of uncertain origin but inhabitants of the warmer waters such as Anodontia, Sunetta, Sinum, Erato s.l., Pollia, Persicula, Scaphander and Belosepia.

5. The development of the corals with the notable abundance of Turbinolia and Sphenotrochus; and above all, the invasion of the Nummulites.

Thus the fauna is once more enriched and renewed. Gervillia is the only remaining remnant of the characteristic Mesozoic elements, aside from such stable types as Nucula, Spondylus and Chlamys. It is also evident that exchanges between the North American seas and those of the Paris Basin have become more difficult and more indirect.

VII. Lutetien

The Lutetien marks the paroxysm of subtropical conditions and confirms, paleontologically, the exuberance of the forms which southern immigrants may assume. Many of the introduced genera were present in the Cuisien, in the Basses Pyrenees near Gan and were already awaiting, so to speak, the possibility of a push toward the North. Harpa and most of the tropical cones penetrated the northern province at this time and the Nummulites like the corals burgeoned.

VIII. Bartonien

The Bartonien does not record an increase in warm water conditions although there is no reversion to temperate sea. The fauna is much less rich and colder than that of the Oligocene. Another regime is established and the filling of the Paris Basin a little later determines the times of arrest of the migrations. (Julia Gardner).

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Répartition actuelle des Mollusques marins envisagée comme base d'appreciation pour les geologues: Soc. Geol. France, Bull., 5th Sér., vol. 13, pp. 441-458, 1943.

Each genus and each species has its geographic and bathymetric limits. The range of the marine molluscan species is generally rather wide, more so than of the terrestrial mollusks. When a generic range is discontinuous, it is commonly a residual form such as the Pleurotomarias in the deep water of the Antilles and Japan and the Pholadomyas of the Antilles and west Africa.

Limiting causes: Temperature is the most important factor in limiting the range of species. The larvae are generally less resistant than the adults and their range consequently narrower. Each species has its thermic maximum and minimum boundaries and also its optimum range of temperature. Dwarfing is common in boundary forms, for example in the Canaries, the southern limit of a number of temperate species such as Venus verrucosa, Pectunculus glycymeris, Meretrix chione and Turritella triplicata.

Preferred food is a second important factor in limiting the range of marine species. Littorina obtusata lives largely on the Fucus, Helcion pellucidum on laminarians and Tridacna and Magilus preferably on coral reefs. The associations play a major role; the organisms are interdependent and a break in the equilibrium may change the geographic limits of the species.

Certain species occupy effectively the entire area in which life is possible; for example, the circumpolar species Acmaea testudinalis and the Australian tropical form, Arcularia dorsata. Others fluctuate, probably because of climatic conditions within their potential range.

An exposition of the factors controlling the distribution of marine molluscan life is given. Among the most important are temperature and preferred food supply which involves the interdependence of the organisms and their community relations. The occasional invasion of the brackish waters by marine species and fresh waters by brackish species is also discussed. Man

has become an active agent in the dissemination of the marine mollusca, witness Crepidula fornicata introduced with oysters on the north European and British coasts and Dreissensia polymorpha endemic in the Caspian sea and now living in most of the rivers of Europe. Most of the living shells occupy a much restricted habitat, the rocks, sand, mud, algal pastures, coral reefs, etc., but after death the shells may be transported by wave or current action or flotation and intermingled to a considerable degree. In the older accumulations of shells, it may be difficult to separate the successive time units and those shells living in neighboring zones. This may however be done in faunas laid down in quiet waters.

Bathymetrically, a threefold division is commonly made: the littoral or intertidal zone; the neritic zone which is penetrated by light and commonly extends to the margin of the continental shelf or to a depth of 200 to 500 meters. Beyond the neritic zone lies that of the ocean deeps. The littoral faunas are the most localized and include the rock dwellers and those of the algal and lichen zones, for the most part, gastropods. The neritic zone is rich both in individuals and in species, both gastropods and pelecypods, and has been subdivided into several zones characterized by the prevalent organisms. Toward the geographic limit of their habitat, the littoral species commonly descend to the neritic zone and thus are protected slightly by their new habitat. Fossil beaches may be identified by rocks covered with sessile animals or perforated with borings of various organisms. Lithodomus, Pholas and Jounnetia perforate rocks or coral but Lithophaga is more commonly found at the outer margin of the intertidal zone. Pholad borings are circular in section while those of Lithophaga are oval and carinate. The deep water shell accumulations include pelagic forms such as pteropods and exiles from the neritic zone. They are usually thin shelled with little color or ornamentation. Syndesmya profundorum has been taken at a depth of 5,270 meters though shells below 2,000 meters are rare. Although these forms are now living in very cold water, few of them are descendants of Arctic species but seem rather to be descendants of Tertiary or older forms that took refuge in the barren depths where competition with other life was at its lowest.

Some of the living biogeographic regions have clear cut limits but more commonly, they present transition zones. In eastern Australia, where the neritic faunas are temperate in character, the intertidal assemblage exhibits a tropical influence particularly marked in the middle and lower horizons. In the Canaries, the littoral faunas are tropical while the neritic are temperate. At Spitzenbergen, the neritic faunas are polar in character while the littoral faunas are cool temperate. These examples show that in shell heaps, it is necessary to separate the littoral from the neritic species before making deductions on the climate. (Julia Gardner).

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The molluscan assemblage of the great fresh-water Lake Tanganyika in west-central Africa is unique in that normal lacustrine species are living in the same habitat together with species resembling those of marine origin and of Jurassic age. The hypotheses advanced to account for these anomalies are, for the most part, modifications of one or the other of the two following theories:

1. The anomalous species in Lake Tanganyika are modified marine types.
2. The anomalous species in Lake Tanganyika are modified lacustrine types.

The arguments of the advocates are given largely by direct quotation. Those of the first school, which are in the minority, include H. Crosse, 1881, who believed Tanganyika represented a former inland sea, and R. T. Gunther, 1893, who believed it to have been a great arm of the Atlantic Ocean extending inland to cover the great basin of the continent. J. E. S. Moore, 1898, and H. Nicolas, 1898, who considered it a relict Jurassic sea, went so far as to suggest faunal affinities between given species.

Advocates of the second school proposed a number of factors that might have been effective in the development of the abnormal species, but they did not explain adequately why all the shells were not equally influenced. The lake water is potable, but it is commonly much disturbed and releases gases charged with mineral vapors that come from great depths in the lake (J. R. Bourguignat, 1888). The bivalves, many of which live buried in the mud and live largely on plankton, will naturally be less affected than the gastropods, many of which are carnivorous. The taste of the water is somewhat alkaline and unpleasant, but there is no evidence that it is saline. J. Cornet (1896) maintained that the "pseudo-marine facies" was nothing more than an adaptation imposed by a body of water comparable in dimensions and depth to a great inland sea and lashed by storms and tempests of comparable severity. Louis Germain, 1908, believed that the Tanganyika fauna had assumed a marine aspect because of the character of the lake in which they lived. He does not explain, however, why similar "pseudo-marine" faunas are not developed in other African lakes of equal surface.

Ernst Stromer (1901) believed with Cornet that Tanganyika was no relict sea, but he considered an "adaptation to a mileu" too facile an explanation. Convergence, isolation, salinity, and atavism might, he thought, be equally important factors. Stromer was one of the few who confessed ignorance and counseled an open mind. Dr. E. A. Smith, 1904, showed the same reticence.

He noted that none of the pelecypods exhibit other than a fresh-water aspect and asserted that in order properly to interpret the thick shells of the "thallassoid" gastropods something of the nature of the environment in which they lived must be known, whether in rivers, deep and calm lakes, or in shallow and disturbed lakes.

W. H. Huddleston, 1904, categorically dismisses the hypothesis of a relict sea on zoological, paleontological, and geological evidence but offers no alternate theory. Paul Relseneer, 1905, C. F. Ancey, 1906, Louis Germain, 1908, W. A. Cunnington, 1920, and Major M. Conolly, 1931, have disagreed with Moore and have offered theories that are, for the most part, modifications of those gone before. Pilsbry and Bequaert, 1927, who made an exhaustive species by species study, maintained that "on the whole, the most plausible explanation of the peculiarites of the Tanganyikan mollusk fauna seems to be that it is a mixture of several distinct faunae, all derived from fluviatile ancestors, but which have reached the lake at different epochs of its geologic past." E. de Martonne (1932) and L. Cuénot (1932) believed that the "thalassoides" fauna might have lived equally well in the rivers and in the lakes and have converged toward the marine types possibly because of the physical chemical conditions in the lake. V. E. Fuchs (1936) introduced a new element into the current theories. Because of the apparent relationship between some of the Mollusca of Tanganyika and those of Lakes Edward and Albert, he believed that an ancestral lake occupied the central African province in the early Pleistocene. Later, toward the close of the early Pleistocene and in the mid-Pleistocene, after the formation of the western Rift Valley, Lakes Edward and Albert dried up, but Lake Tanganyika, because of its great depth, may have become saline but did not disappear. Such a series of events would explain the present differences in the faunas of Lake Tanganyika and of the other two lakes. Possibly, too, the saline waters may have given rise to the thick shells and ornamentation that characterize the "thallassoid" species. The succeeding period of high precipitation again filled the lake, and in it a normal fresh-water fauna was evolved. Other later writers have added little to the general conception of the problem. The authors close with a quotation from Huddleston: "Le probleme du Tanganyika reste irresolu." (Julia Gardner).

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PALEOECOLOGY OF THE EARLY ORDOVICIAN SEA IN CENTRAL TEXAS[1]

by

Preston E. Cloud, Jr.[2] and Virgil E. Barnes[3]

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Table 1. Stratigraphic column for the Llano uplift, Texas
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[1] Report based on work done under cooperative arrangement between the U. S. Geological Survey and the Bureau of Economic Geology of the University of Texas. Published with the permission of their respective directors.

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ABSTRACT

Valid paleoecologic inference demands consideration and proper interpretation of both paleobiologic and sedimentational data. With this in mind we have attempted to correlate the observed lithologic and biologic features of the Lower Ordovician rocks of central Texas with an existing environment. The rock sequence in question is entirely of limestone and dolomite (commonly cherty) and is known as the Ellenburger group. It is divided, from bottom to top, into the Tanyard, Gorman, and Honeycut formations, each formation including both limestones and dolomites.

A consideration of recent sediments potentially comparable to Ellenburger rocks leads to the conclusion that the sublithographic limestones of the Ellenburger group originated as chemically precipitated calcium carbonate muds such as the aragonite muds today forming west of Andros Island on Great Bahama Bank. They are thus calcipulverites, calcipelites, or hydrocalcilites (Grabau, 1913, p. 283, 297) and not calcilutites (idem., p. 285, 290), a matter to be kept in mind by adherents of Grabau's genetic terminology for sedimentary rocks.

It is thought most probable that the dolomites of the Ellenburger group were formed from alteration of calcium carbonate muds at or below the sea floor and during diagenesis. Penecontemporaneous alteration involves interaction between such muds at the sea floor and magnesium compounds in solution or suspension in the basal layer of sea water. Later diagenetic alteration probably follows zones of permeability, with a preference for zones of persistent aragonitic composition in the muds, leading to the irregularity of dolomitization and abruptness of transition to limestone shown by the more coarsely granular dolomites. The dolomites of the Ellenburger group indicate shoal waters at the place of formation, either at the time of deposition (penecontemporaneous) or after burial (later diagenetic) of the calcium carbonate muds which became dolomitized. Variations in the chemical equilibrium of the waters are likewise suggested by dolomitization, and especially by alternation of limestone and dolomite beds; but available information on the chemistry of dolomitization does not warrant specific speculations on this point.

The cherts of the Ellenburger group appear to be roughly divisible into those that originated with the original sediments and those of complex origin. Euhedral dolomite crystals and dolomolds in the chert and the texture and structure of the chalcedonic cherts suggest origin as gelatinous silica in the sediments. The spongy and highly quartzose dolomoldic cherts are probably of complex origin, with much of the quartz druse being secondary. The fact that in the Lower Ordovician rocks of the United States, abundant chert is characteristically associated with dolomite, with chemically precipitated limestones, and with a dominantly molluscan faunal facies is probably a significant phenomenon the basis for which is not understood.

Disseminated quartz sand-grains are essentially absent from the lower third of the Ellenburger group (Tanyard formation), most abundant in the middle third (Gorman formation), and also locally common in the upper third (Honeycut formation). The sand is believed to be wind-blown. Its increasing abundance toward the southern and eastern parts of the Llano region seems to indicate that land lay to the south and east of the Ellenburger marine province.

Ellenburger biotas include a fairly large number and variety of gastropods and cephalopods, occasional trilobites and brachiopods, two genera of bivalved crustaceans, the chaetetid coral Lichenaria (R. S. Bassler iden.), isolated plates of cystoids and chitons, the dasycladacean alga Rhabdoporella (J. H. Johnson iden.), and colonies of blue-green algae through whose metabolic and sediment-binding activities stromatolites were formed. Soft-bodied mud-ingesting organisms were probably fairly abundant in Ellenburger strata, for faecal pellets are common at most stratigraphic levels. It is inferred that, although there were probably times of widely endemic benthonic biotas, many of the Ellenburger fossils were transported after death from local colonies of living shelly benthon in areas of firm bottom to surrounding areas of soft lime-mud. Faunal changes at the formational boundaries are held to be best explained by eustatic or epeirogenic fluctuations, for essentially similar and contemporaneous faunal changes are widespread in the central and eastern United States.

The algally-formed stromatolites are considered indicative of shallow waters, and, as the waters were doubtless commonly turbid with suspended flocculent lime-mud, the average depth was probably quite shallow, perhaps less than 15 fathoms, with the bottom at times locally awash. Sedimentary structures such as dessication polygons (mud cracks) and ripple marks are in keeping with this suggestion.

A consensus of sedimentational and paleobiologic evidence indicates that the Ellenburger province of the mid-Continent sea was (1) marine; (2) shallow, grading from shoal-water conditions at the south and east to somewhat deeper waters at the north and west; (3) warm; (4) well oxygenated; (5) intermittently turbulent and turbid; (6) soft-bottomed at most times and places; (7) firmer-bottomed toward the west than at the east; (8) bordered by land at an unknown distance to the south and east; (9) visited by wind-blown sands in Gorman and Honeycut time; (10) varied as to depth, temperature, and chemical environment, both geographically and in time; (11) affected by eustatic or epeirogenic de-levelings during the transitions from Tanyard to Gorman and from Gorman to Honeycut time; (12) locally colonized by abundant shelly benthos whose dead shells were at times widely distributed by moving water, but at times also supporting more widely distributed endemic biotas; (13) inhabited by numerous soft-bodied mud-ingesting organisms, perhaps jawless polychaete annelids; and (14) closely comparable to the sea of the Great Bahama Bank west of Andros Island.

The report concludes with a comparison between the inferred attributes of the Ellenburger sea and those of the Late Cambrian sea of central Texas and other Early Ordovician provinces of the mid-Continent sea.

INTRODUCTORY STATEMENT

Paleoecology is the study of relationships between ancient environments and their biotas. Valid inference as to the nature of paleoenvironments demands consideration and proper interpretation of both paleobiologic and sedimentational data.

On one hand, it is necessary to inquire whether the faunal assemblages essentially represent preserved natural communities (biocoenoses); or, as in the case of some so-called "dwarf-faunas" (Cloud, 1948b), whether they are but mechanical aggregates of organisms already dead at the time of movement to the

place of burial (thanatocoenoses). Either type of assemblage may be useful and significant in paleoecologic studies, but it is important to recognize and insofar as possible to maintain the distinction.

On the other hand, the nature of the original sediments is indicative of the environment under which they formed and came to rest, and this is a significant aspect of paleoecology. Few ancient strata, however, are preserved for present study in their original condition whose nature and source it is desired to know, and the student of paleoecology here comes to face the commonly complex problem of lithogeny. In its simplest terms the genesis of unmetamorphosed sedimentary rocks involves the following three closely related considerations: (1) under what conditions were the original source materials formed and brought to rest; (2) what was the nature of the original sediments so-formed; (3) through what diagenetic processes, acting at what time, did the rocks in question attain their present lithologic characteristics. The basic data, of course, are those concerning the present state of the rocks in question, so that a logical order of investigation in the field and laboratory is more or less the reverse of that given above; but all phases of lithogeny are interrelated.

The present discussion concerns the life and environment of the Early Ordovician sea in central Texas. The region specifically considered is the Llano uplift, a basinlike structural uplift at the geographic center of Texas (Fig.3). In this region about 4,400 square miles of older Paleozoic and pre-Cambrian rocks have been exposed by doming and erosion of the overlying younger Paleozoic and Cretaceous strata. The Lower Ordovician rocks of the Llano dome are known as the Ellenburger group and have been described in Publication 4621 of the University of Texas (Cloud and Barnes, 1948).

The present report is an outgrowth of a preliminary paper on the paleoecology of the Early Ordovician of central Texas (Cloud and Barnes, 1946) and is an attempt to improve the earlier discussion. Toward this end data and speculations on lithogeny have been added (with appropriate revision, condensation, or amplification) from the above-mentioned report on the Ellenburger group of central Texas (Cloud and Barnes, 1948). The authors have added also an interpretive sketch of Early Ordovician paleogeography in Texas (Fig. 3), a small-scale map of the Bahama Banks region (Fig. 2), a columnar table of formations (Table 1), and some new discussion.

In the following pages an attempt is made to correlate the observed lithologic and biologic features of the Ellenburger rocks with an existing environment. Because the most cogent paleoecologic criteria concerned in this discussion are lithologic ones and the biotas are too sparse and as yet too poorly known to warrant extensive specific analysis, the bulk of the paper is concerned with lithogenic considerations. Of course this discussion is open to qualification throughout its speculative sections.

ACKNOWLEDGMENTS

This paper has profited from discussions carried on orally and by correspondence with a large number of colleagues and associates over a period of five years (1943-1948). To the many who have helped in this way we express appreciation.

TABLE 1.—STRATIGRAPHIC COLUMN FOR THE LLANO UPLIFT, TEXAS*

CENOZOIC	Surficial deposits of Pleistocene or Recent age					
MESOZOIC	CRETACEOUS	LOWER CRETACEOUS	Fredericksburg group	Edwards limestone *(Bluff-forming cherty limestone)*		
				Comanche Peak limestone *(Non-cherty limestone)*		
				Walnut clay *(Thin calcareous clay)*		
			Trinity group	Glen Rose limestone *(Interbedded limestone and marly beds)*		
				Travis Peak formation *(Red and yellow sand, sandy limestone, and shale)*		
	TRIASSIC AND JURASSIC Unknown					
PALEOZOIC	PERMIAN Unknown					
	CARBONIFEROUS	PENNSYLVANIAN	Canyon group or series *(Interbedded limestones and marly shales)*			
			Strawn group or series *(Sandstone and siltstone)*			
			Smithwick shale *(Dark fissile shale with interbeds of dark limestone)*			
			Marble Falls limestone; unrestricted, Morrow equivalent at base *(Mostly dark and cherty limestone)*			
		MISSISSIPPIAN	Barnett formation *(Dark fissile to lumpy shale grading westward to white limesands)*			
			Chappel limestone *(Olive-gray to rose-pink crinoidal limestone)*			
			Unnamed shale and phosphatic limestone of local occurrence in Blanco County			
			Ives Breccia *(Chert breccia and conglomerate)*			
			Unnamed limestone, in part below and perhaps laterally equivalent to Ives breccia			
	DEVONIAN	UPPER (?) DEVONIAN	Zesch formation *(Siliceous limestone)*			
		MIDDLE DEVONIAN	Bear Spring formation *(Cherty limestone)*			
		LOWER OR MIDDLE DEVONIAN	Stribling formation *(Cherty limestone)*		?— *Unnamed siliceous rock float only* —?	
		LOWER DEVONIAN	Pillar Bluff limestone *(Non-cherty limestone)*			
	SILURIAN Unknown					
	ORDOVICIAN	LOWER ORDOVICIAN	Ellenburger group *(Limestone and dolomite non-glauconitic, low in terrigenous detritus)* *(Limestones light gray to almost white, uniformly pure and sublithographic in texture where not transitional to dolomite)* *(Dolomites microgranular and varicolored to coarse-grained and white)*	Honeycut formation 680 max.	*(Complete development has interbedded limestones and dolomites below, mostly dolomite in middle third, and mostly limestone above; dolomites predominantly fine-grained to microgranular; chert occurring intermittently throughout)*	
				Gorman formation 470′ avg.	*(Includes both calcitic and dolomitic facies, limestone ordinarily occurring in the upper part, with dolomite below; dolomite predominantly microgranular to fine-grained; chert occurring intermittently throughout)*	
				Tanyard formation 590′ avg.	Staendebach member *(230–480 ft.; cherty; includes both dolomitic and calcitic facies; dolomites predominantly fine- to medium-grained)*	
					Threadgill member *(90–295 ft.; sparingly cherty to almost chert-free; includes both calcitic and dolomitic facies; dolomites predominantly medium- to coarse-grained)*	
	CAMBRIAN	UPPER CAMBRIAN	Wilberns formation 580′ avg.	Pedernales dolomite member	*(Intergrading facies; 280 feet composite average thickness; dolomites microgranular to coarse-grained, limestones granular to sub-lithographic; glauconite abundant to absent)*	
				San Saba limestone member		
				Point Peak shale member *(160 feet average, green shale, interbeds and bioherm ls.)*		
				Morgan Creek limestone member *(120 feet average, granular, glauconitic)*		
				Welge sandstone member *(18 feet average, sparingly glauconitic)*		
			Riley formation 680′ avg.	Lion Mountain sandstone member *(37 feet average, highly glauconitic)*		
				Cap Mountain limestone member *(280 feet average, granular, glauconitic)*		
				Hickory sandstone member *(360 feet average, non-glauconitic)*		
PRE-CAMBRIAN	Varied metasedimentary and igneous rocks of the basement complex					

* Note: Not to scale

We should like, however, to make special acknowledgment for constructive criticism and encouragement received from John Rodgers, Philip B. King, Mrs. E. B. Knopf, Josiah Bridge, and Harry S. Ladd.

NATURE AND SUBDIVISION OF THE ELLENBURGER GROUP

The incomplete sequence of Lower Ordovician carbonate rocks known as the Ellenburger group includes, from the base up, the Tanyard, Gorman, and Honeycut formations, each comprising both calcitic and dolomitic facies. It is essentially equivalent to the lower half of the Lower Ordovician sequence of the Ozark uplift of Missouri and Arkansas. Outcropping Ellenburger rocks younger than the Jefferson City dolomite of the Ozark uplift are unknown. The Ellenburger has its maximum development at the surface in the southeastern corner of the Llano uplift where it is 1,820 feet thick. It thins to only 830 feet in the northwestern corner of the region, mainly by pre-Devonian truncation, but in part by westward thinning of the Tanyard formation. The rocks of the Ellenburger group are essentially nonglauconitic, and, at most places, are sparingly fossiliferous. Its limestones are dominantly sublithographic and very light gray, the purer ones commonly being in the upper part of the section. Its dolomites range from microgranular to coarse-grained; the coarser grained, paler ones ordinarily being in the lower part of the section, with the finer grained, more brightly colored ones above.

Table 1 shows the position and relation of the Ellenburger units in the stratigraphic column for central Texas, and Figure 1 is a diagrammatic representation of lateral changes in the Ellenburger group and underlying Upper Cambrian Wilberns formation.

The carbonate rocks that overlie the Ellenburger group are nondolomitic, typically dark in color, commonly granular, and may contain organic remains in relative abundance. The limestones of the Upper Cambrian in central Texas are ordinarily granular, glauconitic, and darker in color than those of overlying Ellenburger; and the dolomites in most places are darker in color and finer in grain than the immediately superjacent dolomites of the Ellenburger.

The basal third of the complete Ellenburger sequence constitutes the Tanyard formation, correlative with the Gasconade dolomite and Van Buren formation of Missouri. The Tanyard averages 590 feet thick, thinning westward. The Threadgill member constitutes its lower part, and the Staendebach member its upper part. The dolomites of the Threadgill member are medium- to coarse-grained, and the distribution of limestone and dolomite is irregular. Dolomite predominates, except in the western part of the Llano region where the member is wholly limestone. The dolomites of the Staendebach member are dominantly fine- to medium-grained. The member is wholly dolomite at places in the western part of the Llano uplift; but, to the east, erratically occurring limestone is conspicuous and locally dominant. Chert is rare in the Threadgill member, or consists of principally drusy and dolomoldic types. The Staendebach member, especially toward the east, differs from the Threadgill in containing compact cherts that weather smooth and shiny white. Much of this chert in the Staendebach is oolitic. With rare and inconspicuous exceptions, grains of quartzsand are absent from the Tanyard formation. The Tanyard fauna is dominated by gastropods and cephalopods.

The Gorman formation, correlative with the Roubidoux formation of Missouri, comprises the middle third of the Ellenburger group. It averages 470 feet thick. Dominantly microgranular to very fine-grained dolomite constitutes a lower dolomitic facies except in the northwestern corner of the uplift, where the grain size of the dolomite is coarser, and where erratic lateral transition to calcitic rocks occurs. The upper half of the formation is principally limestone, with a median intrafacies[4] of dolomite coming in eastward, and with the uppermost limestones unusually pure and thickly bedded. The chert of the Gorman formation is apt to be chalcedonic to porcelaneous. Sand is a characteristic feature of the Gorman formation--not as well-defined beds but as scattered to abundant grains in dolomite, limestone, or chert. Where sand occurs in Ellenburger rocks, it constitutes presumptive evidence but not positive proof that the strata are younger than the Tanyard formation. Moreover, it suggests that they are older than the lower 50 feet of the Honeycut formation. Relatively large low-spired gastropods are the most conspicuous fossils in the Gorman formation. The lithistid sponge Archaeoscyphia has been found in the Gorman formation only near its middle, at many places essentially dividing the calcitic facies above from the dolomitic facies below.

The upper third of the Ellenburger sequence, essentially correlative with the Jefferson City dolomite of the Ozark uplift, is called the Honeycut formation. It is known to be present only in the eastern part of the Llano region, and there attains a thickness of about 680 feet. It disappears by truncation west of 98° 55' longitude in western San Saba County. Where fully represented it is divisible into three facies, a lower one of alternating limestone and dolomite, a middle dolomitic facies, and an upper calcitic facies. Locally the middle dolomitic facies grades abruptly to limestone. Lithologically, individual samples of limestone, dolomite, or chert are very like those of the Gorman formation. Sand grains are much less common than in the Gorman formation, and are rare at most places above the lower 50 feet. Ceratopea and Archaeoscyphia are locally common and some beds containing them are useful local datum-markers. The fauna of the Honeycut formation is dominated by gastropods of many sizes and shapes, and the sponge Archaeoscyphia. Trilobites are commoner in the Honeycut than in lower Ellenburger strata except in the upper 100 feet of the Tanyard formation.

RECENT SEDIMENTS POTENTIALLY COMPARABLE TO ELLENBURGER ROCKS

Factors limiting analogy

Inasmuch as carbonate sediments capable of forming dolomites without the addition of magnesium are not known to be forming anywhere in the world today, the probable origin of the limestones of the Ellenburger group is here primarily considered. The dolomites are reserved for discussion under "Genesis of the lithologic constituents."

4/ The expression intrafacies is here used to denote a subordinate facies development within a differing major facies expression. Earlier (Cloud and Barnes, 1946, 1948) we tried to adapt Caster's term parvafacies (Caster, 1934, p. 21-22; Allan, 1948, p. 7-8) to this use with inappropriate results.

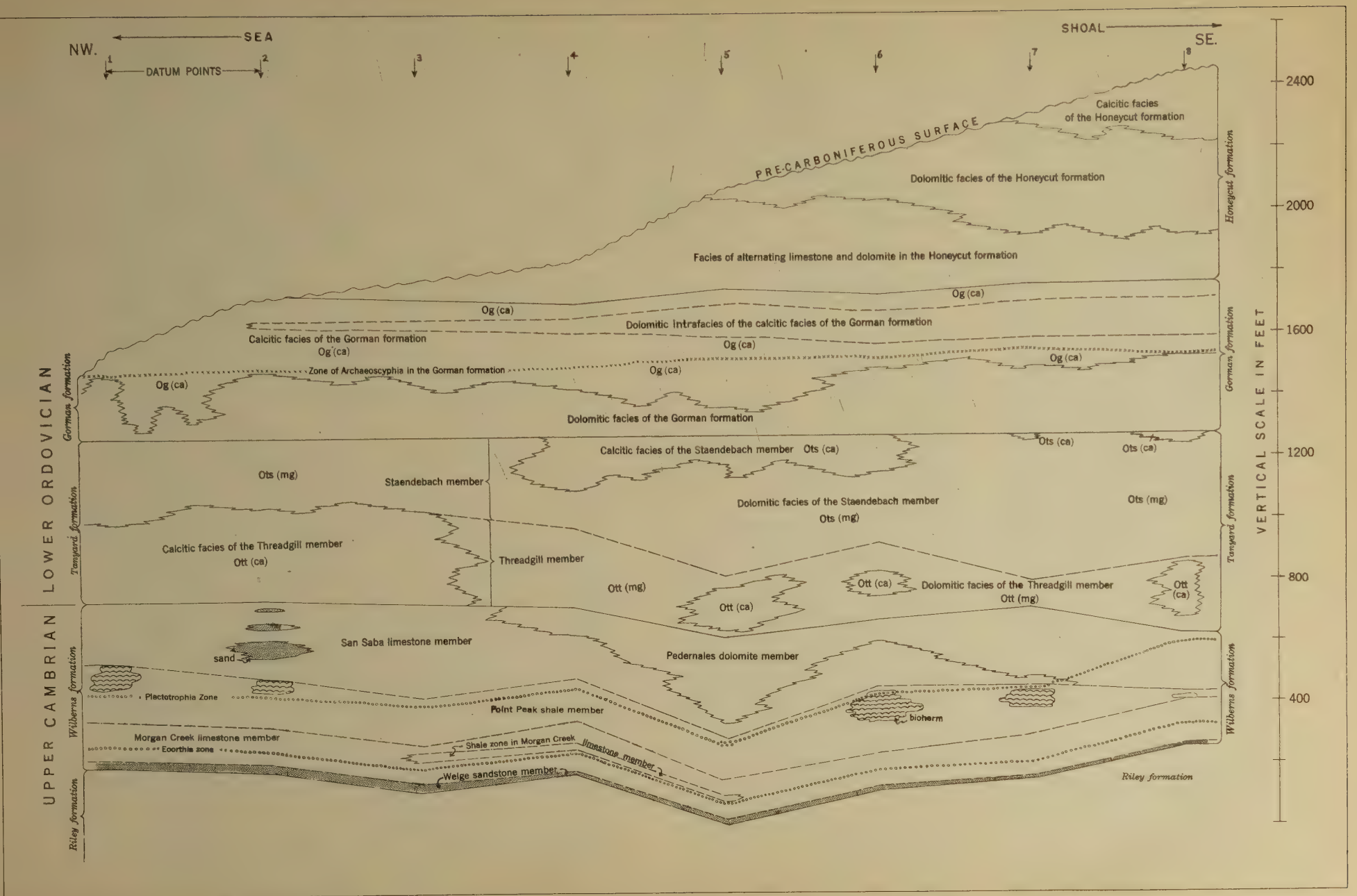

Fig. 1.– DIAGRAMMATIC REPRESENTATION OF THE ELLENBURGER GROUP AND WILBERNS FORMATION IN THE LLANO UPLIFT OF CENTRAL TEXAS

(Datum is contact of Tanyard and Gorman formations)

The typical limestone of the Ellenburger group is a calcite rock so extremely fine-grained that it is described as sublithographic. It may contain minor irregular argillaceous films, patches of limestone pellets, and local small patches or veinlets of calcite. Above the Tanyard formation it locally contains scattered sand grains, and chert is intermittently abundant above the lower part of the Tanyard formation. Glauconite is extremely rare and, for practical purposes, the rock is nonglauconitic. Where it does not break along the minor argillaceous films, its fracture is smooth and almost conchoidal. Terrigenous materials of any sort are scarce in limestones of the Ellenburger group. Silt grains are the dominant terrigenous contaminant, and it is probably significant that the limestones of the Threadgill member of the Tanyard formation contain a greater proportion of silty material in the western part of the region than they do in the east.

At the present time, although calcium carbonate occurs very widely in recent marine sediments even accounting for about 32 percent of deep sea sediments (Vaughan, 1924a, p. 312-313), places where it is being formed in sufficient purity to comprise a potential limestone are restricted. Biogenic and clastic accumulations, such as coral and algal assemblages and their associated clastic debris, colonies of other sessile benthos, coquinas or shell-breccias, limesands, and Globigerina- or pteropod-ooze, account for most modern accumulations of relatively pure calcium carbonate. Obviously, the sublithographic limestones of the Ellenburger group do not belong with any of these although algae may have played a part in their deposition. In fact, the field of the chemically precipitated calcium carbonate sediments must be searched in order to find similarities with limestones of the Ellenburger group. Inasmuch as the Ellenburger fossils demonstrate an essentially marine origin, only sediments formed in or in close association with marine waters are here considered.

It is generally recognized that chemical precipitation of calcium carbonate may occur through the agency of either physical (physiochemical) or biologic (biochemical) processes that disturb the equilibrium of sea waters that are saturated or supersaturated with calcium carbonate. The organic factors have been stressed by some and the physical factors by others, but experimental work shows that both physiochemical and biochemical precipitation can occur. Johnston and Williamson (1916, p. 733) point out that "in order to decide definitely if a natural water is saturated with respect to calcite one must know: (a) the concentration of free CO_2 in water, (b) the temperature, (c) the concentrations of the other constituents present"; and that "of these the third is the only one which has in general been satisfactorily ascertained." However, most investigators now "agree that the surface layers of the ocean water in tropical and subtropical regions are saturated or even supersaturated with reference to $CaCO_3$" (Vaughan, 1924a, p. 325. See also Johnston and Williamson, 1916, p. 735; and Black, 1933a, p. 457). Moberg and others (1934, p. 272) indicate the possibility of relatively heavy supersaturation for the warm surface waters, although they questioned as excessively high, supersaturation ratios such as were derived from data similar to theirs by Wattenberg and other German workers. C. L. Smith (1940, p. 171) says, "It is well known that the surface water of the Atlantic Ocean is heavily supersaturated with calcium carbonate." Revelle (1934, p. 1) states that, "Although the experimental results obtained by various authors for the solubility product are not in agreement, it is at least certain that surface sea water at a termperature of 30°C. is saturated with calcium carbonate."

Calcium carbonate in solution is commonly said to occur as the bicarbonate, $Ca(HCO_3)_2$, although, of course, what is actually present in other than negligible amounts is Ca^{++} ions and HCO_3^{--} ions. The status of calcium carbonate as precipitate or solute is thought to be related primarily to the concentration of CO_2, the pH, and interconnected factors. Calcium carbonate precipitated from the saturated surface waters of the oceans is subject to re-solution where it sinks into cooler waters capable of holding more CO_2, and therefore likely to be undersaturated with respect to calcium carbonate. A natural environment of accumulating chemically precipitated calcium carbonate sediments in the sea is seen to be one of shallow waters in a tropical or semitropical region, where the circulation of the waters is restricted yet sufficient to allow replenishment or replacement from time to time by waters rich in Ca^{++} and HCO_3^{--} ions. The precipitation of $CaCO_3$ through interactions of other soluble compounds involving the sulphate ion apparently may occur in bacterial reactions but is probably not important in the formation of pure calcium carbonate sediments. In any event, continued accumulation, of course, demands continued relative subsidence of the bottom with respect to sea level.

The present known sites of the undoubted occurrence in the sea of chemically precipitated $CaCO_3$, identified by the occurrence of aragonite needles, are the Bahama Banks (many references), "some of the flats behind the Florida Keys" (Vaughan, 1924a, p. 321), "within an inclosed lagoon at Maiao, in the South Pacific" (Thorp, 1936, p. 92), and probably at Funafuti Atoll (Skeats, 1918a, p. 89) and other Pacific Islands (Skeats, 1918b, p. 194). The exact environment of origin at the localities reported by Skeats is not clear, but in the first three instances it is one of shallow, warm, relatively sluggish waters. From what is known of the sediments being formed at these places, those of the Bahama Banks are most nearly like the limestones of the Ellenburger group.

Temporarily reserving comment on the mineralogic composition of the calcium carbonate muds on the Bahama Banks, we may note remarks, inspired by one (Maurice Black) who was intimately acquainted with them, on their probable lithification features: "Aragonite mud behaves, in many respects like a clay sediment. . . . On lithification, the aragonite recrystallises as a dense and tightly welded mass of calcite granules ... and ... shrinkage cracks are formed. These spaces later become filled with (relatively) coarsely crystalline calcite deposited slowly from solution." (Hatch, Rastall, and Black, 1938, p. 174). Black also believed that, "Amongst the older limestones, the calcite mudstones are the lithified representatives of the modern aragonite muds. . . . The purer calcite mudstones are pale grey in colour, and have a smooth, almost conchoidal fracture. . . . Thin sections show that these rocks consist of extremely minute crystals of calcite, the individuals being so small that they render the slice semi-opaque. Running through this fine-grained rock are irregularly branching little veins of clear calcite, in comparatively coarse crystals." (Hatch, Rastall, and Black, 1938, p. 173-174.) The limestones of the Ellenburger group are such rocks.

An environment of origin for the limestones of the Ellenburger group similar to that on the present Bahama Banks is indicated. Needless to say, an isolated "bank" is not required although the Ellenburger sediments could have been formed in an area relatively elevated with respect to the surrounding sea floor. It has been pointed out that the reduced circulation and other conditions on wide shoal-water shelves and banks "resemble in some respects the conditions in

isolated lagoons" (Hatch, Rastall, and Black, 1938, p. 171); and the protected bank areas are, in a sense, evaporating pans. Similar conditions may well have been, and probably at times were, widespread in epeiric seas in shallow areas not receiving quantities of terrigenous sediments, such as might be found far from shore, adjacent to land approaching base level, or separated from the shore by relatively deep, current-swept channels.

Geographic, sedimentary, and biologic features of the Bahama Banks

It may be profitable to examine more closely the geography and sedimentary features of the Bahama Banks to see what sorts of conditions are displayed. Figure 2 is a map of the region, adapted from Chart A of Drew, 1914, with additions from other sources.

From Figure 2 it may be seen that the complex of banks, islands, and intersecting channels of the Bahama Bank region comprises a general shoaly area southeast of Florida and north of Cuba. The banks themselves extend to within 60 miles of Florida and 50 miles of Cuba, but are separated from both by deep channels. The general area involved is kidney shaped, convex at the southwest, and elongated in a north-northwest to south-southeast direction. It is about 450 miles long and 170 miles wide at the middle, tapering bluntly at both ends. Within the general area outlined, about 30,000 square miles consist of "banks" which are today receiving or have recently received precipitated calcium carbonate muds. Those parts of the bank areas that are swept by currents tend to be surfaced by limesands (Black, 1933a, p. 462), but below the seasonably stagnant waters west of Andros Island an area of about 4,500 square miles is known to be floored with deposits that contain a large proportion of aragonite needles (Black, 1933a, p. 461, fig. 1; Field et al., 1931, fig. 1). This area of known aragonite muds is itself about as large as the surface expression of the Llano uplift, and the total area of potential calcium carbonate precipitation is about the size of Maine or one-ninth as large as Texas.

Great Bahama Bank, to the south, is separated from Little Bahama Bank, to the north, by a deep channel. Great Bahama Bank is divided into a smaller eastern and a larger western lobe by a tongue of the ocean. This tongue of the ocean is 120 miles long, averages 25 miles wide, and ranges in depth from 1,200 fathoms at its north end to 756 fathoms at its south end. It is a deep cul-de-sac in a shallow bank. Great Bahama Bank itself is mostly less than 3 fathoms deep, and apparently does not exceed 5 fathoms in depth except on its shelving margins. On the west side of the tongue of the ocean lies Andros Island, 140 miles long in a north-south direction, protecting a large part of the western lobe of Great Bahama Bank from sweeping by currents and thus encouraging conditions favorable to the precipitation of calcium carbonate muds. Little Bahama Bank, on the north side of Providence Channel, is bounded at the south by Bahama Island and at the east by Great Abaco Island. Theoretically the sheltered bank area west of Great Abaco Island should constitute an evaporating pan similar to that west of Andros Island and likewise favoring the accumulation of calcium carbonate muds. The entire shoal area is sharply delimited and drops abruptly "at a gradient of one in three for the upper part of the slope, to depths varying between 2500 and 6000 feet" (Black, 1933a, p. 455).

"According to gravity data the Bahama Block is not underlain by igneous rocks, . . . is approximately in isostatic equilibrium, and has undergone recent

oscillation in relation to sealevel. Structural phenomena on the margins of the block indicate long and persistent fault-zones; the block has risen or is rising on the east and is sinking or has sunk on the west" (Field and others, 1931, p. 783).

Of the sediments Black says (1933b, p. 167): "The rocks which form the islands are very pure limestones of Pleistocene Age, and the modern sediments on the banks are also entirely of calcite and aragonite, without any admixture of siliceous or argillaceous material (Thorp, 1936, p. 82 says--no appreciable terrigenous material) . . . . Andros Island . . . is the largest island in the Bahamas. Along the east coast there is a well developed barrier reef backed by a narrow ridge of limestone hills . . . . Low-lying marshy plains, interspersed with shallow lakes and outcrops of limestone are found in the interior, whilst in the westernmost part of the island . . . the country consists of white, unconsolidated limestone-mud . . . with bare white drewite5/ flats, . . . (and) an intricate system of tidal creeks and mangrove swamps, which render it liable to heavy flooding under favorable circumstances." Drew (1914, p. 33) supplements Black's description as follows: "Towards the west of the island (Andros) the land is remarkably flat, and near the coast consists of white chalky mud, which has partially dried, and in places has formed a harder crust on the surface. These half-dried mud-flats slope almost imperceptibly into the sea, and are continuous with the submarine flats which extend some sixty miles off the coast with an average depth of two to three fathoms. The mud forming these submerged flats is very soft, and near the coast it was easily possible to push a twelve-foot sponge pole down to its full length into it without touching any harder material. The surface layer of the mud for a depth of about 6 inches is of a creamy white color, but below that it is of a grayish tinge and has a slight odor of sulphureted hydrogen."

According to Field and others (1931, p. 774) "the bulk of the fine-grain mud . . . is composed of crystalline grains of calcite and aragonite, 0.05 to 0.01 millimeters, and fine needles of aragonite 0.003 to 0.005 millimeters in diameter." Black states (1933a, p. 461) that "In the centre of the shoals west of North Andros Island, aragonite needles make up about 20 percent of the sediment, the other constituents being shells of foraminifera, chips of mollusc shells, and some limestone grains." References to mud cracks and ripple marks in the submerged muds were not noted, but dessication cracking of the muds on Andros Island is remarked by Black (1933b, p. 183).

"It would appear . . . that an appreciable quantity of the fine-grained calcium carbonate muds in the Bahamas, no matter what their present location, might have originated under fresh or brackish-water conditions" (Field, et al., 1931, p. 777). Bavendamm (1932) shows, on the basis of bacterial counts and other data, that the most favorable areas for the bacterial precipitation of $CaCO_3$ are not in the open sea, but in the marshes, inlets, or mangrove swamps on Andros Island. The inadequacy of a bacterial mechanism to account for the bulk of the lime-muds of the bank area proper, however, is now generally conceded.

5/ Vaughan (1924, p. 316) pointed out that the term "drewite" as originally described by Field (1920, Carnegie Inst. Washington, Yearbook 18, p. 197) was applied to the fine-grained, mostly detrital muds in Tortugas lagoon, and that it is not similar to the mainly chemically precipitated calcium carbonate muds to which Kindle (1923) applied it (Thorp, 1936, p. 80-81) and for which Black here uses it. The lithified end product of a drewite in the proper sense is thus a calcilutite (Grabau, 1913, p. 290); whereas calcite rocks of chemical origin are calcipulverites, calcipelites, or hydrocalcilites (Grabau, 1913, p. 283, 285, 290, 297).

Fig. 2.- GREAT BAHAMA BANK AND ENVIRONS
(after Drew, 1914, with minor additions)

It would also seem that in this region sediments of marine or complex origin may come finally to rest under essentially subaerial conditions. Black (1933b) describes how colonies of sediment-binding algae on the marl flats at the west side of Andros Island trap the calcium carbonate sediments from suspension in waters that are swept over them from the banks to the west during storms. Sediment-binding algae also grow under the shoal waters of the Great Bahama Bank, but "no complex algal heads were observed, and . . . it was only above low-water mark . . . that alga-controlled lamination and algal heads with characteristic internal structures were found" (Black, 1933b, p. 169). Black (1933b) further shows that the structures made by these colonies of sediment-binding algae resemble certain Paleozoic stromatolites (see Cloud, 1942); that different geographic and salinity belts support different growth-forms; that these structures are produced by communities of organisms; that, whereas they may be in part precipitated, they result in large part from mechanical entrapment; and that they originate normally as a surface modification of unconsolidated sediments, with well-developed algal sediments passing laterally and downwards into ordinary bedded sediments. "They mark a borderline facies between land and water -- and, indeed, they often occupy territory which the cartographer hesitates to assign to either. Their structure depends upon several rhythmic processes, foremost amongst which is the alternate flooding and draining of the areas in which the algae grow" (Black, 1933b, p.182).

Ambiguity between what is marine and what is terrestrial seems inevitable in the interpretation of ancient sediments deposited under similar conditions, and the most that can be said is that if the rocks generally contain marine fossils their environment of deposition was essentially marine. On the other hand, even a dominance of nonmarine fossils would not establish a nonmarine depositional environment under such circumstances, as Field et al. (1931, p. 773-774) have pointed out.

The life of the Bahama Banks is described by Field et al. (1931, p. 769, 773) as "that of an area in which but few kinds and small numbers of animals and plants could live." However, they state that the inch-wide burrows of a small crab are "found in abundance wherever the water is more than 4 feet deep." Farther from shore in slightly deeper water, sponges, hydroids, crustaceans, and calcareous algae are reported. The "sponge colonies tend to change their position from year to year, and especially after long and severe storms; and C. L. Smith (1940, p. 150) notes that "Many sponges break off from their original attachment and become 'rollers,' when they occur wherever the currents drift them." According to Field et al., few live mollusks were found, and these only in the deeper areas or holes. Black (1933a, p. 463) notes that "Bottom samples of sediment sometimes consist largely of the shells of benthonic foraminifera and mollusca, but these are mostly decayed or broken, and living specimens are comparatively rare. Bottom living organisms appear to be abundant only where there is an outcrop of bare rock on the sea floor. (Underscoring added) Such outcrops are not frequent and are of small area; where they do occur, they are reported to be colonized by alcyonarians, sponges, and calcareous algae, and to support a fairly rich molluscan fauna. It is probable that much of the dead shell material which is spread over the rest of the bank has been derived from these comparatively well-colonized areas." (Underscoring added) Twenty to 50 miles east, on the eastern shore of Andros Island, "where there is practically no calcium carbonate mud, extremely abundant and diversified life exists" (Field et al., 1931, p. 777).

The chemical precipitation of calcium carbonate from saline waters

In 1892 Dall (in Dall and Harris, p. 101) suggested that much of the calcium carbonate mud in the shoal waters of the Florida keys "is probably the result of deposition of lime originally in solution and precipitated by chemical action." Subsequent authors have generally accepted chemical precipitation of calcium carbonate in the sea as a fact, although disagreeing on the relative importance of various processes in bringing it about. A good account of the situation is given by Black (1933a); a brief summary account by Hatch, Rastall, and Black (1938, p. 170-173); a more extensive summary by Twenhofel and others (1932, p. 311-328); and a theory of physiochemical precipitation is outlined by C. L. Smith (1940).

A large amount of experimental and empirical evidence has been brought to bear on the problem of solubility of $CaCO_3$, $CaSO_4$, and $MgCO_3$ in the presence of one another in sea water, yet their solubility limits under varied conditions are not clearly understood. Empirical data suggest that calcium carbonate is the least soluble of the three salts in sea water under ordinary conditions. Wallace (1927, p. 65) states that "$CaCO_3$ is relatively insoluble, (and) $MgCO_3$ relatively soluble" in saline waters, and the absence of bedded gypsum in normal marine sediments indicates that its solubility limit is not exceeded above the sea floor in normal marine environments (interstitial gypsum probably originates authigenically from connate waters, through bacterial or physicochemical agency). "The large difference between the solubility product constants of calcium carbonate in sea-water and in pure water is explained as being partly caused by the low activity coefficient of the carbonate ion in sea-water" (Moberg et al., 1934, p. 273).

There follows a systematic tabulation of some of the factors that have been advanced to account for chemical precipitation of calcium carbonate from sea waters.6/ Naturally some overlap is involved in both theory and probable application of these factors. Moreover, although all of the effects tabulated below can be written chemically in terms of balance of the basic equilibria:

$$H_2O \rightleftharpoons H^+ + OH^-$$

$$H^+ + HCO_3^- \rightleftharpoons H_2O + CO_2$$

$$HCO_3^- \rightleftharpoons H^+ + CO_3^{--}$$

$$Ca^{++} + CO_3^{--} \rightleftharpoons CaCO_3$$

the situation is actually much more complex than these simple equations might suggest.

In simple terms, any factor, such as 1A, 1B, or 1C below, that causes shifts in equilibria that increase the CO_3^{--} ion concentration at the expense of HCO_3^-

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6/ We are indebted to Prof. J. J. Lingane of the Chemistry Department of Harvard University for help with the final arrangement of this tabulation.

ion concentration, tends to cause the precipitation of $CaCO_3$ (fourth equation above). Similarly the addition of carbonate ion (1E below) causes precipitation of $CaCO_3$ (fourth equation above).

I. Physicochemical factors

A. Removal of CO_2 from sea waters containing Ca^{++} and HCO_3^- ions.
   (1) By rise in temperature of the water, decreasing the solubility of CO_2.
      (a) Through warming of waters upwelled from the depths, by mixing with surface waters, and by insolation.
      (b) Through rise in temperature of superjacent air currents.
   (2) By agitation of the water.
   (3) By escape to air currents low in CO_2.
   (4) By lowering of total pressure.

B. Evaporation; resulting in increased salinity, and loss of CO_2 because of decreased solubility of CO_2.

C. Variations in hydrogen ion concentration; interconnected with other physicochemical factors and representing changes in CO_2 tension and variation in concentration of the CO_3^{--} and Ca^{++} ions. The exact results of direction of displacement of equilibria are complicated by factors whose effects are not agreed upon. (Irving, 1926; Wallace, 1927; Moberg et al., 1934; Smith, 1940).

D. Disturbance of equilibrium by differences in the partial pressure of CO_2 in the sea and in the air above it, resulting in overbalancing or piling up of the Ca^{++} ion and precipitation of $CaCO_3$ (Lipman, 1924, p. 190; Gee et. al., 1932). Related to A, and especially to A (2) and A (3).

E. Addition of a strong alkaline carbonate or bicarbonate to solutions saturated with $CaSO_4$ or $CaCl_2$. For example $(NH_4)_2CO_3$, K_2CO_3, or Na_2CO_3 may combine with $CaSO_4$ according to the equation $R_2CO_3 + CaSO_4 = CaCO_3 + R_2SO_4$; R being a monovalent alkaline base (Vaughan, 1924a, p. 314).

II. Biochemical factors

A. Removal of CO_2 from sea water by normal life processes of plants.

B. Bacterial activity.7/
   (1) By ammonifying or nitrate-reducing bacteria.

$$NH_3 + H_2O = NH_4OH$$

$$2NH_4OH + Ca(HCO_3)_2 = CaCO_3 + (NH_4)_2CO_3 + 2H_2O$$

7/ The reactions tabulated are those conventionally listed. Actually all could be expressed essentially in terms of the basic equilibria given above; for the whole process, unless and until precipitation actually occurs, is simply one of ionic interbalance and none of the compounds written is actually present in sea water as such in more than negligible quantities. Chemically it is obscure to write the equations in the conventional manner, but it takes less space and is probably more readily comprehensible to the non-chemist to present them in this way.

$$(NH_4)_2CO_3 + CaSO_4 \cdot 2H_2O \rightleftharpoons CaCO_3 + (NH_4)_2SO_4 + 2H_2O$$

$$(NH_4)_2CO_3 + CaCl_2 \rightleftharpoons CaCO_3 + 2NH_4Cl$$

$$2NH_3 + Ca(HCO_3)_2 \rightleftharpoons CaCO_3 + (NH_4)_2CO_3$$

(2) By sulphate reducing bacteria.

$$CaSO_4 + 8H \rightleftharpoons CaS + 4H_2O$$

$$CaS + CO_2 + H_2O \rightleftharpoons CaCO_3 + H_2S$$

Drew's hypothesis of precipitation by a single bacterial agent (1913, 1914) is now generally discredited, and it has been shown by Lipman (1924) that bacteria probably do not precipitate any significant quantity of calcium carbonate in the open sea. The stimulus of Drew's work, however, led to investigations by Bavendamm (1932) that appear to sustain the importance of bacteria in the precipitation of calcium carbonate from saline waters under certain special conditions.

In summary, the published record seems to warrant the following assumptions: (1) in general, warm waters of the modern sea are saturated or supersaturated with calcium carbonate; (2) under normal conditions in recent seas calcium carbonate is less soluble than magnesium carbonate, and the solubility limit of calcium sulfate is not exceeded above the sea floor; (3) factors affecting the concentration of CO_2 in a given volume of sea water are of primary importance in the chemical precipitation of calcium carbonate; (4) under special conditions not ordinarily found in open sea water, bacteria can and probably do precipitate calcium carbonate; (5) the exact role of hydrogen ion concentration, other than as an index to the concentration of CO_2 and CO_3^{--} will bear further analysis; (6) chemically precipitated calcium carbonate, in order to be preserved as a potential rock-forming sediment, must come to rest at a place where it is not subject to resolution or mechanical removal; (7) considering known factors, the most favorable environment for the accumulation of deposits of chemically precipitated calcium carbonate is one of warm, shallow, relatively sluggish waters where sea bottom is undergoing slow but continued subsidence.

As Vaughan (1924a, p. 328) aptly puts it: "The purest limestone is a very shallow water deposit. . . . Whether a shoal-water deposit is a pure limestone or not (however) is determined not by depth of water but by outwash from the land." The normal organic and detrital limestones are relatively shallow neritic or even littoral deposits, and the deep-sea oozes are in a special and stratigraphically insignificant category.

The ancient calcite mudstones, exemplified by the sublithographic limestones of the Ellenburger group, were probably formed predominantly by physicochemical processes in warm shallow seas. Such rocks, a small but important minority of known limestones, are especially characteristic of parts of the Lower Ordovician in North America.

Mineral nature of chemically precipitated calcium carbonate in recent seas

It is of interest whether calcium carbonate that is chemically precipitated from sea water comes out of solution mainly as the metastable mineral aragonite

or as the stable mineral calcite; and, if the former, how long it may persist in that state under various conditions.

Vaughan (1924, p. 317-321) described the naturally precipitated aragonite needles (identified by H. E. Merwin) from the Bahamas as being "particles so minute as to be visible only with a very high power of the microscope or the ultramicroscope." The smaller aragonite needles are said to exhibit vigorous Brownian movement and probably to consist of particles of colloidal size (3 to 5 microns according to Field et al., 1931, p. 774). Chemically precipitated calcium carbonate sediments are identified chiefly by the presence of aragonite needles. Samples from the Florida Keys also contain aragonite needles, but they are much fewer; and many of the small particles from the Floridian muds appear to be rhombs and are believed to be calcite.

Between 1914 and 1942 no less than 12 different authors or groups of authors called attention to the natural occurrence of aragonite in marine calcium carbonate muds, and its occurrence has been independently confirmed by at least 7 of these authors. Moreover, aragonite needles have been reported from calcium carbonate sediments at Maiao in the South Pacific (Thorp, 1936, p. 92) and probably at Funafuti and elsewhere in the Pacific, as well as at several localities in the Floridian and Bahaman regions. Thus it seems well established that aragonite is precipitated from marine waters without the intervention of unusual processes.

The oceanographic conditions under which aragonite muds may form and accumulate in quantities sufficient to be potentially rock-forming appear to be rare today and to have been so at most times in the past. Comparison of results of bottom sampling with data on the rate of sedimentation (Black, 1933a, p. 458-461) suggests that the aragonite needles in the modern calcium carbonate muds retain their mineralogic character for a reasonably long period of time. In the core from Funafuti, according to Skeats (1918a, p. 89), aragonite is common from near-surface portions of the core but decreases with depth, is practically absent at 150 feet, and was not recognized below 220 feet. It thus appears that marine aragonite (with sulfate as an impurity) does not quickly invert to calcite, but retains its mineral identity for an unknown but perhaps geologically significant length of time. Bøggild (1930, p. 244, 238) writes that, "In the Alpine Triassic we may find shells (of molluscs) possessing a perfectly unaltered aragonite," but that, "the aragonite of all Paleozoic and many younger shells has been changed entirely into calcite." Comparable data on the relative span of persistence of aragonite needles in calcareous muds would be of particular interest in connection with the problem of dolomitization. In any event no reliable report of pre-Triassic aragonite is known to the authors[8/].

Johnston, Merwin and Williamson (1916, pp. 483, 501, 509) have discussed the transformation of aragonite to calcite. They point out that the rate of transformation of pure aragonite in contact with water is slow at ordinary temperatures,

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8/ A reported occurrence of original aragonite in a middle Pennsylvanian pelecypod (Newell, N. D., Late Paleozoic pelecypods; Pectinacea: Kansas Geol. Surv., vol. 10, p. 26, 70, 1938) was based on a staining technique considered unreliable by mineralogists and needs to be restudied. The nacreous layer of orthoceroid cephalopods from the Upper Ordovician near Dubuque, Iowa, gives the x-ray powder pattern and optical properties of a carbonate apatite. (Dr. Clifford Frondel, personal communication to Cloud, 1947).

but is accelerated by the presence of calcite, and by increase in temperature. They further point out that the presence of sulfate in marine aragonite may be responsible for the precipitation as aragonite rather than as calcite, and also may retard the conversion to calcite after precipitation. They further speculate that aragonite may even be really stable in contact with the natural waters in which it formed.2/

The actual proportion of aragonite to calcite in the chemically precipitated calcium carbonate muds is not clear from the published record. Evidently aragonite is not abundant in them except in parts of the Bahaman region. It is also not clear whether any of the calcium carbonate is actually precipitated as calcite or whether all the calcite in these sediments is detrital or secondary.

In 1914 (p. 54) Vaughan maintained that the calcium carbonate muds of the Bahamas were "precipitated mostly as aragonite," and Twenhofel and others (1932, p. 314) cite Vaughan as authority for the statement that "the calcium carbonate precipitated is mainly, if not wholly, in the form of aragonite." Black (1933a, fig. 1; see also Field et al., 1931, fig. 1) found the bottom deposits that "contain a high proportion of aragonite mud" to be localized in an area of about 4500 square miles in the lee (on the west side) of Andros Island. Black (1933a, p. 460-461) describes this as "an area where the sea is floored by a deposit consisting largely of aragonite mud," but goes on to say that, "In the centre of the shoals west of Andros Island, aragonite needles make up about 20 percent of the sediment." Then Hatch, Rastall, and Black (1938, p. 171) say that "a considerable area of the sea floor west of Andros Island is covered with a white deposit of precipitated aragonite," which they proceed to describe as aragonite mud. Thorp (1936, p. 94) states that "aragonite needles are distributed over most of the area studied (Bahama Banks), but it appears that they have been washed from one or two local regions of precipitation." It is thus not clear whether these sediments at places do consist predominantly of aragonite, or whether they are called aragonite muds because of the large proportion of aragonite in them. In any event 20 percent of any sediment is a considerable proportion, and even if that proportion is not actually exceeded on the Bahama Banks, there is no evident reason why sediments comprised largely of aragonite could not have been important in the past.

GENESIS OF THE LITHOLOGIC CONSTITUENTS OF ELLENBURGER ROCKS

Limestone

The limestones of the Ellenburger group are remarkably free of terrigenous materials, and where they are not dolomitic or cherty, they are essentially pure calcite rocks. Material of terrigenous origin in the limestones of the Tanyard formation is virtually limited to minor argillaceous material increasing westward, and to very minor amounts of angular silt particles especially in the most westerly outcrops. With rare and very inconspicuous exceptions sand is

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2/The presence of strontium, varium, or lead would probably also tend to favor the initial formation of aragonite and to retard its conversion to calcite. Data are insufficient to evaluate the importance of this factor.

absent from the Tanyard. The argillaceous material occurs as irregular films and not as well-defined layers. The limestones of the Gorman and, less commonly, of the Honeycut formation are intermittently and sparingly arenaceous. The well-rounded and evenly frosted quartz-sand grains which they contain are ordinarily scattered through thin zones in the carbonate rock and seldom make well-defined sand beds. It is argued on a following page that they were probably brought to their present position by the wind, and that their source was probably to the east and south of the present outcrops in the Llano uplift.

Except where they have been pelleted by mud-ingesting organisms, where they contain irregular veinlets of clear crystalline calcite, or where they are dolomitic, the texture of these limestones is that of the finest lithographic stone. Where they do not break along the irregular argillaceous films, their fracture is subconchoidal. The limestones consist of crystals of calcite so minute that thin sections appear semi-opaque. In fact, the calcite crystals' average diameter of 0.002 to 0.005 mm. as determined from thin section, is startlingly close to the 0.003 to 0.005 mm. given as the average range in diameter of aragonite needles from the Bahama Banks by Field et al. (1931, p. 774).

It can hardly be doubted that the bulk of the limestones of the Ellenburger group were originally chemical precipitates. In fact, they may have been purer chemical precipitates than the calcium carbonate muds of the Great Bahama Bank itself where, in the center of the shoals west of North Andros Island, aragonite needles make up only 20 percent of the sediment, with "other constituents being shells of foraminifera, chips of mollusc shells, and some limestone grains" (Black, 1933a, p. 461).

Comparison of the lithologic features of limestones of the Ellenburger group with the inferred potential lithologic features of recent marine sediments suggests their origin through alteration, probably at or near the sea floor, of sediments chemically precipitated as aragonite. They might thus be thought of as penecontemporaneous or diagenetic calcite rocks, derived from physical alteration of primary calcium carbonate source muds of aragonitic composition. Some alteration to calcite might have occurred during partial reworking of the muds, in which case particles so altered would have been calcite at the time of their last settling down (primary in the special sense of Sander, 1937). The precipitated muds were worked over by mud-ingesting organisms (Moore, 1933, 1939), patches of whose ovoid faecal pellets resemble structureless oöids. In some of the more fossiliferous strata fragments of shells are locally conspicuous, and some of the beds are intraformational limestone conglomerates or breccias; but nowhere are any significant proportion of the limestones of the Ellenburger group known to be truly detrital. The occasional occurrence of polygonal contraction patterns (mud-cracks) suggests very shallow water and probably actual temporary exposure to the atmosphere. Ripple marks were also observed at a number of places.

Dolomite

The only recent dolomitic materials known to exist in rock-forming quantities are the clearly secondary dolomites of various coral islands in the Pacific and Indian oceans and some of the coral reefs of the Red Sea (Dana, 1849; Skeats, 1903, 1918b; Walther, 1888). Such dolomites may be exemplified by the now

classic Funafuti Atoll in the south Pacific (see Skeats, 1918b; Hatch, Rastall, and Black, 1938, p. 195-197; Twenhofel et al., 1932, p. 342-344), and Skeats has summarized the evidence to show that the dolomites of Funafuti Atoll and other Pacific islands result from post-depositional alteration. In fact, to state a widely held conclusion in the words of Twenhofel et. al. (1932, p. 339), "no examples of primary deposition of dolomite are known and . . . primary deposition of this sediment lies entirely within the realm of theory."

We too are impressed by the general truth of this statement, although it must be conceded that interbedded or intertonguing association of dolomites with evaporite deposits infers a primary origin for such dolomites. It is possible, to be sure, for associated gypsum or/and anhydrite and dolomite to have originated through penecontemporaneous interaction between $CaCO_3$ and $MgSO_4$ (A. von Morlot, 1847, as reported in Dana, 1849, footnote, p. 153-154), but one might expect the result of such action to be a mixture of dolomite and gypsum rather than an interbedded product.

Our views about dolomite, based on field and laboratory studies and a review of the published record, are essentially in accord with those expressed by Van Tuyl in 1916 and were arrived at along similar lines of reasoning. Important views and summaries of information on dolomite, in addition to those of Van Tuyl (1916), are given by Blackwelder (1913), Steidtmann (1911, 1917), Wallace (1927), Murray (1930), Twenhofel et al. (1932, p. 330-351), Sander (1937), and Hatch, Rastall, and Black (1938, p. 175, 183-197). The following points seem worthy of emphasis:

1. Dolomite is known to be formed secondarily along joints, faults, or other zones of weakness or permeability in the sedimentary blanket of the earth's crust by either ground-water leaching or replacement, or by hydrothermal or pneumatolytic action (see, for instance, Hewett, 1931, p. 37-67).

   Dolomitization may extend laterally from such channels along the bedding and become locally conspicuous; but known occurrences of such dolomite are volumetrically unimportant in the geologic column, and hydrothermal or pneumatolytic action cannot account for volumetrically important dolomitization.

   Sherman and Thiel (1939) have shown that circulating ground waters charged with sodium and magnesium are probably today effecting dolomitization 1 to 3 feet below the surface of calcareous silts that were deposited in ancient glacial Lake Agassiz. This unusual situation is thought to approximate the process of diagenetic dolomitization under marine conditions, as suggested in item 4 below. A situation such as that described by Sherman and Thiel could obtain only under very special conditions, the record of which is not commonly preserved in ancient sediments; but it does serve to remind one that dolomite per se is not necessarily indicative of marine origins.

2. The only adequate source of magnesium for most laterally extensive, nonclastic, bedded dolomites is the sea.

3. No examples of primary deposition of dolomite are known among recent sediments, and it is a general truth that the primary chemical precipitation of dolomite muds in the geologic past lies entirely within the realm of theory.

However, direct precipitation of dolomite may well result from evaporation of inclosed hypersaline waters (Skeats, 1905, p. 137, 138; P. B. King, written communication to Cloud, July 2, 1946). Such deposits are typically associated with gypsum and other evaporite salts that clearly represent a special type of sedimentation and require special explanation.

4. Most well-bedded, laterally persistent dolomite between beds of unaltered limestone and not associated with evaporite salts can be accounted for only by penecontemporaneous alteration of calcium carbonate sediments at the seafloor or by primary deposition of the dolomite. However, sure distinction between primary (as distinct from authigenic) and penecontemporaneous dolomite is probably not possible, except to the extent that some dolomite can be shown not to be primary (Cloud, and Barnes, 1948, p. 91). Zoned crystals of calcite and dolomite prove precipitation of dolomite as such, but probably after formation of the sedimentary body in which the crystals are enclosed.

It is known from Steidtmann's work (1917, p. 439) that, "The replacement of aragonite and calcite by dolomite has been effected experimentally at ordinary temperatures by solutions comparable to sea water." Irving (1926, p. 441) points out that "Magnesium hydroxide is precipitated from sea-water by addition of small amounts of alkali," and that "both magnesium and calcium are in delicate equilibrium where slight changes in alkalinity and carbon dioxide tension may cause precipitation." In a personal communication to Wallace (Wallace, 1927, p. 65), Irving states that if increase in alkalinity "results from increase in free base alone, the magnesium is rapidly precipitated as the pH rises above 10," and that "there is a possibility of salt waters naturally approaching a pH value of 10, permitting the precipitation of both calcium and magnesium" (compounds not specified). He also remarks (in Wallace, loc. cit.) that, whereas $CaCO_3$ is relatively insoluble and $MgCO_3$ relatively soluble (in saline waters), "$Ca(OH)_2$ on the contrary is quite soluble as compared with the insoluble $Mg(OH)_2$."

From these and other data it would seem that there is little chance of actual precipitation of $CaMg(CO_3)_2$ in unconfined saline waters except through interaction of $Mg(OH)_2$ or $MgSO_4$ and $CaCO_3$ suspensoids, or as an evaporite (see Skeats, 1905, p. 137, 138; 1918b, p. 185; any association of dolomite with normal evaporite salts such as anhydrite, gypsum, or bittern salts), and less chance of precipitation of pure $MgCO_3$. The published information on the relative solubilities of the various compounds of calcium and magnesium found in sea waters at present appears to favor the deduction that penecontemporaneous alteration of calcium carbonate sediments by magnesium compounds acting at the sea floor is a more probable dolomitization process than is primary precipitation. In view of this, the writers hold that it is not advisable to assume a primary origin for a dolomite that can as well be explained as the result of penecontemporaneous alteration.

Nolan (1935, p. 22) also argues for the penecontemporaneous origin of pre-Carboniferous dolomites in the Gold Hill quadrangle in Utah; and Skeats (1918b, p. 192) argues that dolomitization of certain calcareous sediments "followed so closely on its formation as to be almost contemporaneous with it in a geologic sense." The idea of dolomitization during diagenesis was

apparently originated by J. D. Dana in 1849 (p. 153) to explain dolomitization of elevated coralliferous rocks from the island of Metia (or Matea, or Aurora) in the Paumotu (Tuamotu) Islands of the south-central Pacific.

5. It has been known since 1848 (Van Tuyl, 1914, p. 361) and is now well established that dolomite may grade laterally to limestone with great abruptness.

   As a rule such dolomite is coarse-to fine-grained, and it is commonly vuggy or porous. Such dolomites may be underlain and overlain by limestone, but the lateral contacts between limestone and dolomite are likely to be gradational. It is thought that most such dolomites were formed below the sea, but probably at greater depth and at a later stage in diagenesis than the penecontemporaneous dolomites. Dolomites so formed would be truly secondary dolomite, but secondary within the diagenetic cycle and not as a result of ground-water leaching. Both penecontemporaneous and later diagenetic dolomites are, of course, authigenic.

6. A scatter-diagram by Steidtmann (1917, p. 437, fig. 1) based on "1,148 analyses of specimens from all over the United States . . . shows that nearly pure limestones and dolomites are more common than mixtures of the two."

   Doubtless analyses across transitional zones would show a transitional character although they might not affect the conclusion drawn from Steidtmann's data by Twenhofel et al. that "conditions which favor dolomitization in the sea appear to be rather sharply distinct from those which do not permit it."

7. Inasmuch as "aragonite and other metastable forms of $CaCO_3$ react much more readily with chemicals than does calcite," and a rock that consisted mainly of metastable $CaCO_3$ "would be in a very favorable condition to be dolomitized" (Van Tuyl, 1916, p. 401; see also Hatch, Rastall, and Black, 1938, p. 191), it is of special interest that aragonite is volumetrically important in recent chemically precipitated calcium carbonate muds west of Andros Island in the Bahamas. Aragonite muds were probably volumetrically important among the source elements of sublithographic limestones in the past, and distribution of aragonite in the original sediments may have some relation to irregular dolomitization of the rocks and to lateral gradations not related to apparent zones of vertical circulation.

   The experiments of C. Klements, as cited by Skeats (1905, p. 136; see also 1903, p. 63-64; 1918b, p. 186-187) showed that under pressure (actually high pressure), and at a temperature of 90 to 100°C. for a period of one to two days, calcite, aragonite, and aragonitic organisms kept in solutions saturated with NaCl and $MgSO_4$ underwent selective dolomitization. "Calcite took up only a trace of magnesium carbonate, aragonite absorbed 38 per cent, and corals and other aragonitic organisms over 41 per cent. The chemical instability of the aragonite was here the determining factor in the rapidity of interchange." Skeats (1918b, p. 192) also shows that there is a selective preference for aragonite in dolomitization under natural conditions.

8. The porosity of many of the coarser grained dolomites is probably related to the greater potential permeability offered leaching solutions by their coarser fabric and to minor irregularities of initial dolomitization.

Among the dolomites of the Ellenburger group there is a general tendency for the finer grained dolomites of the Gorman and Honeycut formations to average slightly higher in $CaCO_3$ than those of the Tanyard formation. It is suggestive that the dolomites with the higher calcite ratio are also those of finer grain and lower porosity, but more extended observations are needed on this matter before a conclusion may be reached about this relationship. The presence of coatings of well-formed dolomite crystals in some of the vugs suggests recrystallization from leaching solutions. The observations of the present writers lead them to view favorably the suggestion of Murray (1930, p. 463) that dissolution of included calcite from dolomites by percolating waters is important in developing porosity.

9. It has been observed by many geologists, including Hatch, Rastall, and Black (1938, p. 192), P. B. King (written communication to Cloud, July 2, 1946), and the present writers, that rocks that are dolomites near ancient lands are prone to grade to limestones away from the old shorelines.

The explanation for this is probably to be found in the fact that experimental evidence shows that dolomitization is favored by elevated temperatures and that, other conditions being equal, "dolomitization goes on most favorably in those regions where the waters are warmest" (Van Tuyl, 1914, p. 402). Dolomitization should, therefore, be encouraged by shallowness of water and thus nearness to shore or shoal areas (see also Twenhofel et al., 1932, p. 346). Independent evidence of a shallow-water origin for dolomite is found in associated textural features (Skeats, 1918b, p. 196, 200; Nolan, 1935, p. 22-23; Steidtmann, 1911, p. 338; and others); and Skeats (1903, p. 65-66; 1905, p. 138 and preceding; 1918b), apparently the original proponent of the idea, has summarized evidence to indicate that dolomitization is favored by shallow waters.

10. If, as Skeats (1905, p. 134) and later workers (e. g. Raymond, 1925; Nolan, 1935, p. 22-23) have inferred, the degree of dolomitization is related to the length of time during which the original sediments were exposed at the sea floor, rate of subsidence and burial could have important effects on results produced. For instance, alternating limestones and dolomites, such as are prominent in the lower part of the Honeycut formation, or rythmic dolomitization (Sander, 1937) might be accounted for by mechanisms invoking these factors.

However, we are inclined to believe that duration of exposure is not as important to dolomitization as the chemical constitution of the basal layer of sea water and the permeability of the sediments. This is suggested by selective dolomitization of trails in the Tanyard formation of the western part of the Llano uplift and burrows that occur locally in the characteristically pure limestone of the upper bed of the Gorman formation. The burrows and the faunal discontinuity at the latter horizon indicate that the bed in question remained exposed at the sea floor for a much longer time than beds of dolomite immediately above it in the Honeycut formation. Of course, other things being equal, time of exposure at the sea floor might relate to degree of dolomitization. Thus the commonly observed relation of dolomitization to unconformities may tie in with duration of exposure although we suppose it to be more probably determined by the fact that

development of an unconformity is surely preceded by shoaling and thus probably warming of waters.

Proceeding from the foregoing, the following genesis is suggested as probable for the dolomites of the Ellenburger group.

The dolomites that show abrupt lateral transitions to limestone through considerable stratigraphic intervals, including all of the medium-and coarse-grained dolomites and some of the fine-grained ones, are secondary or later diagenetic dolomites. They were formed from calcium carbonate sediments below the sea floor at a stage in diagenesis sufficiently advanced for some compaction of the sediments to have taken place. Some of their abrupt lateral transitions to limestone may be related to zones of transition between calcite and aragonite in the sediments being altered, but others are probably related to zones of permeability in the original sediments. Partial dolomitization resulted in limestones with an irregular internal meshwork of dolomite, or the reverse, and patches and grains of calcite remained locally in almost completely dolomitized sediments. The porosity now visible in these dolomites resulted largely from leaching, mainly of relict calcitic inclusions, by slowly percolating meteoric waters at some date subsequent to their lithification.

The dolomites that are laterally persistent, especially where they alternate with limestones, were probably formed penecontemporaneously at the sea floor. Penecontemporaneous origin involves reaction between original calcium carbonate muds at the sea floor and magnesium compounds in solution or suspension in the basal layer of sea water. The dolomite beds that are laterally continuous include nearly all the microgranular to very fine-grained dolomites and some of the fine-grained ones. Because of the relative solubilities of the carbonates and hydroxides of calcium and magnesium and because even some of the microngranular to very fine grained dolomites do grade abruptly to limestone at a few places, the writers think of them as penecontemporaneous (see also Cloud and Barnes, 1948, p. 91). It is conceivable in theory, however, that a current from which carbonate minerals were being precipitated might locally be sufficiently depleted of $CaCO_3$ or have its pH increased to such an extent as to permit the precipitation of $CaMg(CO_3)_2$, while $CaCO_3$ continued to precipitate in adjacent parts. In any event it cannot be said positively that the dolomites here called penecontemporaneous are not in part primary, and to that extent a sense of query is implicit in the use of the adjective "penecontemporaneous." Ideas similar to those of the present writers have previously been suggested by Daly (1909, p. 170), Blackwelder (1913, p. 622), Hatch, Rastall, and Black (1938, p. 175), and others.

The scattered euhedral dolomite rhombs seen in many of the limestones of the Ellenburger group probably resulted from reactions at the sea floor with waters not having a sufficient excess of magnesium for more extensive dolomitization, or from crystallization from connate waters in the unconsolidated sediments.

No dolomites of clastic origin are know among the rocks of the Ellenburger group in the Llano region.

Chert

It is difficult to escape the inference that much, if not all, of the chalcedonic to porcelaneous chert of the Ellenburger group was penecontemporaneous or primary in origin, and that the interstitial chert results mainly from diagenetic redistribution (interstitial confinement) of disseminated silica in the sediments.

Observations by the authors in the field and laboratory indicate that the dolomoldic cherts, which are so commonly regarded as true epigenetic cherts, result from intense leaching of dolomites that contain quantities of interstitial chert. Such cherts are commonly laced with crystalline quartz druse, resulting from redistribution of disseminated silica by meteoric waters, and making the total weathered mass more compact and bulky than one finds among residues prepared from fresh, relatively unleached rock. Their origin is, therefore, complex. The concentrated growth of quartz druse on jointing and bedding surfaces, in vugs, and in the cavernous or vuggy dolomoldic cherts clearly betrays its secondary origin. It is ordinarily localized in the dolomitic rocks, suggesting a relation to permeability. The idea of origin by redistribution of disseminated silica is supported by studies of insoluble residues from Upper Cambrian limestones and dolomites (San Saba limestone and Pedernales dolomite members of the Wilberns formation) that are equivalent to one another. These show a minimum of crystalline quartz particles and a maximum of disseminated silt or dust particles in the limestones, whereas the reverse is true in the dolomites.

Silicification of fossil shells is an open problem. It seems most unlikely that this could occur within sublithographic limestones through weathering, but silicified shells are not known from Ellenburger rocks of the sub-surface.

The chertification of pellet limestones, oölites, and stromatolites - like that of fossil shells - is clearly post-depositional, but may have been penecontemporaneous with and not too long after sedimentation.

The occurrence of well-formed dolomolds and dolomite rhombs in many of the nodules, lenses, and beds of compact cherts suggests their origin through aggregation of silica at the sea floor, concomitantly with the dolomitization process. The fact that chert textures can be used at all in stratigraphic studies suggests their relation to sedimentary or early diagenetic processes or both.

An origin as semi-gelationous silico-calcareous mud balls is suggested for the so-called "cannonball cherts" of the Honeycut formation (Cloud and Barnes, 1948, p. 16). Their features suggest origin by rolling about at the sea floor of plastic material that incorporated and bonded lime-mud and fragments of loose shells in a sticky matrix, much as a snowball may be built up by rolling on the snow-covered ground.

It is perfectly conceivable that such mud balls might be rolled by intermittent current or wave action insufficient to disturb significantly the sticky impalpable lime-muds that probably comprised the floor of the Ellenburger sea over most of central Texas. The drifting by currents of sponge "rollers" on

the Bahama Banks has been described by Smith (1940, p. 150), and it is certain that the wide distribution of pieces of the lithistid sponge Archaeoscyphia at certain levels in the Ellenburger group was attained in a similar manner. Archaeoscyphia "rollers" and cannonball chert are common associates in the upper part of the Ellenburger. Moreover, evidences of intermittently turbulent conditions are found sporadically through the Ellenburger sequence, and especially above the Tanyard formation, in the form of local thin intraformational granule breccias and conglomerates. Differences in density of sponge and mud ball and the "rubbery" nature of silica gels are objections to the idea outlined. The first is inconsequential if one has subspherical mud balls and motion of any significance in the waters above. The second, it is hoped, will be minimized by mixing a lot of calcium and water in with the silica.

The various stages of apparent chertification of these cannonball cherts is probably related to varying original silica content, with possibly some redistribution of silica related to areas already partially siliceous. The concentration of fossils in these cannonballs, in general contrast to the surrounding limestones, supports the origin suggested and negates the counterhypothesis that they may be concretionary. Some of them apparently were compressed to lobate masses while yet plastic, if the sublenticular material of this texture did not result from accumulation and binding of drifting material in depressions originally present, but many retain a subspheroidal form.

Quartz-sand

Quartz-sand, ordinarily referred to simply as sand, is found in the Ellenburger group in rocks younger than the Tanyard formation. It occurs typically as scattered grains in carbonate rocks and seldom comprises well-defined sand beds. In the Llano region the rocks of the Gorman formation are more commonly and more abundantly arenaceous than those of the Honeycut, and the lower 50 feet of the latter are more commonly arenaceous than the overlying part of the formation. The sands become more numerous and volumetrically more important from west to east and from north to south in the Llano region. The most prominent sand known to occur in Ellenburger rocks is a 21-inch zone that outcrops in the old Lake Victor quarry, about 13 miles north of Burnet, in Burnet County. At this place 8 to 8.5 inches of slightly dolomitic sandstone is overlain by 12.5 to 13 inches of dolomite with half-inch layers of dolomitic sandstone like the lower 8 inches. In the lower 4.5 inches of this 21-inch zone are subrounded to rounded dolomite pebbles as much as 2.5 inches long and 0.8 inch thick.

The individual grains of sand are typically well-rounded, evenly frosted, small, and poorly sorted within their small size limits. Grains that barely exceed the size limit of silt are commonly quite as well rounded and smoothly frosted as larger grains.

We believe that most, if not all, of this sand was brought to its present position by the wind. Evidence supporting this view is as follows:

1. The generally well-rounded, smoothly frosted condition of even the very small grains, some as small as 0.06 mm. being recorded from the lower strata of the Gorman formation in the Warren Springs section, indicates that they were shaped if not transported by wind action.

2. The sand grains of most of the arenaceous zones are scattered and poorly sorted within their small size-limits, and the arenaceous intervals are thin and widely intermittent.

3. The general scarcity of terrigenous sediments of all sorts in the Ellenburger rocks poses obvious difficulties to the alternate hypothesis of water-borne transportation from the land.

4. The common association of sand zones with evidence of locally turbulent water conditions, suggests an association with windstorms. This is exemplified by the occurrence noted at the Lake Victor quarry (above), where sizable pebbles of dolomite occur in the lower part of a prominent zone. These pebbles were probably little more than compacted muds when they were torn loose from the sea bottom, which accounts for their subrounded to rounded condition.

5. The competency of winds to carry sand is well demonstrated, and wind-borne sands are well known in recent marine sediments. Hatch, Rastall, and Black (1938, p. 26) describe an area lying southwest of the coast of Africa between Cape Verde and the Canary Islands, where "During the spring and winter months a surprisingly large area of sea floor . . . receives a considerably amount of wind-transported material . . . (that) consists principally of well-rounded grains of quartz and is accompanied by much fine dust." Sand storms at sea are common off the coast of southern California, where they are locally known as "Santa Anas".

Glauconite

Although glauconite is common in many of the Upper Cambrian rocks of central Texas, it is an exceedingly rare mineral in rocks of the Ellenburger group, and its occurrences in the Ellenburger are probably not authigenic. Being a mobile mineral, however, it has locally attained an interstitial relationship with dolomite. Glauconite is recorded locally from the lime-muds of the Bahama Banks by Thorp (1936, p. 83), who states that "the very few grains in these deposits appeared to be old, eroded, and definitely not of authigenic origin." It is not known whether glauconite originates through alteration of pre-existing biotite at the sea floor (various papers by Galliher), from alteration of "a number of mother materials" (Takahashi, 1939), or as a flocculent precipitate on the sea-floor and not by alteration of other minerals (Hadding, 1932). Regardless of its initial origin it seems more often than not to have been pelleted by bottom-feeding organisms; resulting in its polished and ovoid to lobate form, and probably in some enrichment in potassium.

The distribution of probably authigenic glauconite in the lower Paleozoic rocks of the Llano region is of paleoecological significance. Therefore some environmental implications that have been attributed to glauconite are given:

1. "Glauconite is essentially a mineral of marine environments, and although it may find its way as a detrital mineral into terrestrial and fresh-water deposits, there is no satisfactorily confirmed case on record of its having been actually formed in a non-marine environment" (Hatch, Rastall, and Black, 1938, p. 141; and similar statements in most references listed).

2. Glauconite orginates typically in neritic environments (permanently submerged sea bottom less than 100 fathoms deep), and it probably does not form in littoral environments (shore zone between tides).

   Hatch, Rastall, and Black (1938, p. 142) say that "Greensands and green muds in modern oceans are found near the edge of the continental shelf, though the mineral glauconite occurs in both deeper and shallower water." They think (op. cit. p. 143) that, where evidence of deposition in very shallow waters is found, "it seems probable that in many of these instances the glauconite was not formed contemporaneously, but was deposited in the form of a secondary concentrate." Hadding (1932, p. 54) thinks that, "beds of glauconite were deposited at a depth of probably less than 100 m., and the formation of glauconite took place at the same slight depth." In Monterey Bay, just south of 37°N. latitude on the coast of California, Galliher (1935a, p. 1353) found that "Glauconite begins to occur in the sediments together with biotite at depths as little as five or ten fathoms; and . . . finally, at about fifty fathoms, glauconite becomes very abundant and fives the sediments a dark greenish cast."

3. Hadding (1932, pp. 54, 159) supposed that glauconite formed in "relatively cold water," basing his supposition on, among other things, the fact that it "neither occurs nor has been formed ... with the coral reefs, nor in bryozoan beds." Takahashi (1939, p. 504) points out that "A summer temperature of not lower than 15° C ..... seem(s) necessary for glauconitization". Galliher, however, (1935b, fig. 16) indicates glauconite to occur in recent sediments at virtually all latitudes from the equator to 65°S and 80°N. Thus it would seem that glauconite is not a reliable temperature index, although it may suggest waters that were not markedly warm.

4. On stratigraphic evidence Hadding (1932, pp. 54, 84, 160) suggested that "beds of glauconite were deposited and the glauconite formed in agitated open water."

5. Hadding (1932, pp. 54, 160) believed that "The formation of glauconite was favored by a slightly reducing milieu," and that it "never formed in highly oxygenous water."

6. Galliher (1935a, p. 1361) states that "Recent occurrences of glauconite, as recorded by several writers (5 publications cited), always lie adjacent to land masses where plutonic or metamorphic complexes are exposed to erosion." Figure 16 of Galliher, 1935b, shows "Glauconite in present ocean basins," indicating its general proximity to igneous or metamorphic rocks. However, most of the coast line of the world, except in the Arctic regions, is shown to be of or near igneous or metamorphic rocks and the validity of Galliher's implication is not unequivocably substantiated.

7. Abundance of glauconite may be suggestive of abundance of organisms at the place of its formation. Conway (1945, see especially p. 595, 600) has argued that return of potassium from sea water to sediments - probably at least a phase of glauconitization - is facilitated by organic processes and by the acids produced by decaying organic matter (related to item 5).

This inference is borne out by the fact that much glauconite appears to have been organically pelleted, and by the common abundance of other organically derived castings and of fossil shells or fragments of them in association with glauconitic sediments.

FOSSILS OF THE ELLENBURGER GROUP

Tanyard formation

The biota of the Tanyard formation is dominated by gastropods and cephalopods, many of them large. A dasycladacean alga, a primitive colonial coral, a few brachiopods, occasional trilobites, and an archaeostracan crustacean also occur.

The gastropods Lytospira gyrocera (Roemer), Ophileta polygyrata (Roemer), and Gasconadia cf. G. putilla (Sardeson) dominate the relatively thinly bedded limestones of the Threadgill member of the Tanyard formation in the western part of the Llano region. The upper 90 to 100 feet of the Tanyard is characterized by the dasycladacean alga Rhabdoporella (determined by Dr. J. Harlan Johnson, letter to Barnes, 10/29/45), the primitive chaetetid coral Lichenaria (determined by Dr. R. S. Bassler, oral communication), two species of the trilobite Paraplethopeltis, two species of the bivalved archaeostracean crustacean Ribeiria, several species of the brevicone cephalopod Clarkoceras, and an abundance of the almost planispirally coiled gastropod Ozarkina.

The brachiopod Tetralobula is known only from about 40 to 50 feet above the base of the Tanyard formation in the western part of the uplift. The only other brachiopods known from the Tanyard formation are Syntrophina and Finkelnburgia, the former being rare, and the latter at some places common. Finkelnburgia obesa Cloud holds a position about 260 to 285 feet above the base of the Tanyard formation in the Bear Spring area, and F. helleri Cloud is locally abundant near the base of the formation in the western part of the Llano region.

The breviconic cephalopods Dakeoceras, Burenoceras, Conocerina, and Levisoceras make their first appearance near the middle of the Threadgill member of the Tanyard; Burenoceras ranging to the middle of the Gorman formation and Conocerina ranging perhaps to the top of the Tanyard, but apparently not into the Gorman formation. Dakeoceras has not been recognized above the lower one-third to one-half of the Staendebach member of the Tanyard. Levisoceras seems to range through much of the upper three-fourths of the Tanyard formation but not to its top. Ectenoceras ranges downward from the top of the Tanyard formation to some point well below its middle. Oneotoceras is rare but diagnostic of the Tanyard formation. It has been seen almost at the top of the formation and at points well toward or below the middle.

To consider the gastropods: Lytospira (formerly confused with Ecculiomphalus), although typically a fossil of the Threadgill member of the Tanyard formation in the western part of the uplift, ranges through the Tanyard-Gorman boundary and well into the Gorman formation. Although Ophileta ranges through the Tanyard and Gorman formations and into the Honeycut, the Tanyard species of Ophileta are commonly large and relatively depressed, both as to spire and cross section

of the whorl. Sinuopea and Schizopea range through or almost through the Tanyard formation and downward into the top of the Cambrian, but the presence of an abundance of specimens suggests the Tanyard. Ozarkina and Helicotoma of the type of H. uniangulata (Hall) range from the top of the Tanyard formation to somewhere well below its middle, and Gasconadia ranges from its base to somewhere above the middle. Chepultapecia ranges through at least the upper half of the Tanyard and into the Gorman formation. Patelliform snails, and the so-called "Pelagiella" paucivolvata (Calvin), are locally abundant. The patellids range through the formation, but the range of "P." paucivolvata has not been determined. A "Euconia"-like snail has been seen at a few places.

Finally, the trilobite Leiostegium occurs in the lower part of the Tanyard formation at some localities, and cystoid and chiton plates are locally common.

Gorman formation

The Gorman formation is not only poorer in number and variety of fossils than the other formations of the Ellenburger group, but proportionately fewer of its fossils have been described. Its most striking faunal elements are the large gastropods Rhombella (formerly known as "Roubidouxia") and Lecanospira, but a number of other gastropods and cephalopods, a few brachiopods and trilobites, and a lithistid sponge are known.

The name Rhombella applies to large, widely phaneromphalous gastropods whose pleural angle ranges from about 90° to 105°, and which consist of about 5 very rapidly expanding whorls that are rhombic in cross section and essentially flat at the top and base. Ordinarily only the two basal whorls are preserved; and parts of at least two whorls are required to distinguish it surely from Euconia, a high-spired shell with 8 or 9 whorls that expand more gradually than those of Rhombella, and with an acute pleural angle (65° to 75°). Small, high-spired, Euconia-like shells with a convex base are designated "Euconia," pending systematic revision. Rhombella occurs from the base to the top of the Gorman formation, and its sure identification probably constitutes proof of a Gorman age.

Lecanospira is known only from the Gorman formation. It ranges from the top of the formation probably to its base but is uncommon in the basal strata. Lytospira and Ophileta are known from the Gorman formation but are not characteristic of it. Ophileta of the type of O. rotuliformis or O. leo (referable, if the refinement is desired, to the subgenus Ozarkispira), however, suggest the Gorman formation; and in general the post-Tanyard ophiletas have higher spires and relatively deeper whorls than do the Tanyard species. Patelliform gastropods are locally common, and some are provisionally assigned to Proplina. Chepultapecia is not uncommon in the lower part of the Gorman formation, although its presence tends to suggest the Tanyard. The high-spired gastropod Hormotoma makes its first known appearance at the base of the Gorman and extends upward through the Honeycut formation. Plethospira also first appears in the Gorman formation, and perhaps Raphistomina and Polhemia.

As for the brachiopods, two species of Diaphelasma mark the upper 90 feet of the Gorman formation (D. oklahomense and D. pennsylvanicum, both of Ulrich and Cooper) and Syntrophina /S. campbelli (Walcott)/ suggests the lower 120 feet of the Gorman, although one Syntrophina has been found about 200 feet below

the Tanyard-Gorman boundary. Syntrophinella is known only from the vicinity of the Archaeoscyphia zone in the Gorman formation where it is represented by S. warreni Cloud.

The lithistid sponge Archaeoscyphia is known below the Honeycut formation only from a restricted interval near the middle of the Gorman formation, and the only species that has been recognized in either formation is A. annulata Cullison.

A few cephalopods are known from the Gorman formation, but most of these have not been identified. The flat-ended siphuncle of Mcqueenoceras occurs locally in the upper half; a large Clitendoceras-like cephalopod occurs in the zone of Archaeoscyphia; and small, strongly curved brevicones having flaring apertures and ranging for some distance below the zone of Archaeoscyphia are assigned to Burenoceras. The piloceratids are represented only by a single siphuncle closely resembling that of Piloceras hornei U. F. M., which was obtained 15 to 20 feet below the Archaeoscyphia zone of the Gorman formation (TF-90).

Of trilobites, species of Hystricurus are most common, but the genus ranges into the Tanyard formation also. An occasional cystoid plate represents the pelmatozoans.

Honeycut formation

Many of the Honeycut fossils of central Texas appear to be specifically identical with fossils described from the Jefferson City dolomite of Missouri by Cullison (1944). The general assemblage is so similar that the slight variations are thought to be mostly geographic. The dominant faunal elements are the sponge Archaeoscyphia annulata Cullison, and species of Ceratopea, Orospira, Hormotoma, and other gastropods of many sizes and shapes. Species of the trilobites Jeffersonia (in the sense of Cullison), Rananasus, and Bathyurellus are common at places in the lower half of the formation, with Rananasus apparently having a fairly restricted range. The flat-ended siphuncles of the endoceratid cephalopod Mcqueenoceras are also locally common.

Except for its occurrence near the middle of the Gorman formation, Archaeoscyphia is known only from the lower half of the Honeycut, but it is there very abundant locally. No specimen has been seen in the position of growth, but occasional joined specimens and their local concentrations suggest that these sponges grew in colonies from a common substratum.

The brachiopod Xenelasma syntrophioides Ulrich and Cooper is known from the lower 140 feet of the Honeycut formation and is common in the lower 70 feet. It occurs mostly in chert, but it is very common as free silicified specimens at places on the top surface or in the top inch or two of the highest stratum of the Gorman formation. It is not known at a lower position, and the "Gorman specimens" probably grew at the sea-floor of earliest Honeycut time. Finkelnburgia of the type of F. cullinsoni Ulrich and Cooper (earlier mistaken by us for Tritoechia) has been found at a few places in the Honeycut formation, and, of course, the commoner "finkelnburgias" of the more generalized types have also been noted.

Six "species" of Ceratopea have been found to characterize particular parts of the section. These are at present designated by number 1 to 6, in the sequence of first appearance, pending description and naming of the new species. Species 5 and 6 (C. "keithi" Ulrich) each display several varieties, and the young of species 3 (C. robusta Oder) are so difficult to tell from species 2 (C. capuliformis Oder) that the two forms are regarded as subspecies of C. capuliformis in the broad sense (in practice they are briefly designated by subspecific name alone). In addition to the six species of Ceratopea that were so helpful in local biostratigraphic studies, Ceratopea tennesseensis Oder has been collected in the Honeycut Bend section from the highest stratum of the Honeycut formation known in the Llano uplift, and a small claw-shaped species is known from the lower part of the formation.

The almost planispirally coiled hyperstrophic gastropod Barnesella lecanospiroides Bridge and Cloud (congeneric with "Maclurea" affinis Billings) has been found only from about 130 to 180 feet above the base of the Honeycut. This pseudosinistral shell is easily confused with Lecanospira but a marked bulge on the inner surface of the whorl, toward the keel, is a distinguishing feature. Raphistomina, Lesueurilla, Polhemia, Plethospira, and patelliform gastropods occur locally, and a possible representative of the sinistrally coiled Onychochilus was seen at one place.

The evolutely coiled nautiloid Tarphyceras cf. T. chadwickense U. F. M. F. has been found between 280 and 400 feet above the base of the Honeycut formation, representing an extension of the genus Tarphyceras into older beds than those from which it has previously been reported. Piloceratid cephalopods are represented by the occurrence of thickly conical siphuncles, probably referable to Allopiloceras, at three localities (T.F.-246, 16T-2-43D, 16T-2-33E) having a range of 460 to 580 feet above the base of the Honeycut formation. The longicone Cotteroceras or a laterally compressed Cyptendoceras was seen at a few places. Aphetoceras and the subterminally aperturate, evolutely coiled Moreauoceras have been collected from the lower part of the Honeycut formation.

The bivalved archaeostracan crustacean Eopteria has been found only from about 130 to 180 feet above the base of the Honeycut formation, holding essentially the same range as was observed for the gastropod Barnesella.

ECOLOGIC IMPLICATIONS OF ELLENBURGER LIFE

The fossil assemblages in rocks of the Ellenburger group are few in number of species and individuals. The faunas are dominantly molluscan, with gastropods and cephalopods relatively well represented. Brachiopods are few in number, only 7 genera and 13 or more species being known from the entire 1,800 feet of rocks that comprise the Ellenburger group. Trilobites are uncommon, but better represented than the brachiopods. Two genera of archaeostracan crustaceans and two of sponges are known, and the primitive coral Lichenaria (identified by R. S. Bassler) occurs near the top of the Tanyard formation. Representatives of other zoologic groups are rare or absent.

Evidence of plant life is limited to stromatolites (see Cloud, 1942), possibly related to the activities of sediment-binding algae (see Black, 1933b), and abundant remains of the dasycladacean alga Rhabdoporella (identified by J. H. Johnson). The latter is known only from the upper 90 to 100 feet of the

Tanyard formation. The ecologic implications of the algal structures are discussed in the papers cited, and summarized in the section that follows.

In their dominantly molluscan aspect the Ellenburger faunas resemble those of correlative carbonate rocks in the Ozark uplift and the southern Appalachian region and differ from those of the Arbuckle and Wichita Mountains, the Marathon basin, and to a lesser extent the Franklin Mountains. They are, of course, markedly different from those of the black shale facies in the Lower Ordovician.

The Ellenburger fossils have not been studied in sufficient detail to say definitely whether they occur in definite zones separated by unfossiliferous rock as Cullison (1945, p. 47, 52) found the Lower Ordovician fossils in the Ozark uplift to do. Some species and genera certainly mark particular zones, but the impression of the writers, based on mapping, is that the fossils in general are erratically and sparingly distributed through much of the section and that, although conditions were in general not favorable to the shell-bearing bottom-dwellers, there were local areas at most times where benthonic or nekto-benthonic shells could and did survive. At some times these conditions were more widespread, and relatively abundant life developed, but it is believed that in most instances this more abundant life was an outgrowth from forms that held on through the unfavorable periods. An analogy is found with conditions on the Bahama Banks today, where a generally soft bottom and waters periodically muddied with flocculent calcium carbonate are unfavorable to most forms of life, but where local patches of solid bottom support a rich molluscan fauna, as well as sponges, corals, and calcareous algae (Black, 1933a, p. 463; also a preceding page of the present report).

Mud-ingesting organisms were active through most of Ellenburger time, as is shown by the commonly pelleted limestones (see Moore, 1933, 1939). These organisms apparently were mostly soft bodied, for preserved shelly remains are insufficient to account for the numbers of animals that must have engaged in the pelleting process. Probably many of them simply plowed up and ingested the surface muds, but others actually bored into the muds and left well-defined burrows such as may be seen locally in the upper bed of the Gorman formation. H. B. Moore (1933, p. 25) believes that the simple ovoid pellets, such as are most common in the Ellenburger rocks, "are those of either polychaetes (marine annelids) or molluscs." Thus, if the inference is correct that the pellets in the Ellenburger rocks were mostly made by soft-bodied organisms, burrowing marine annelids may have been responsible for them. If so, they were probably of jawless types, for scolecodonts have yet to be recovered from these rocks.

Tracks of fossils are common in the relatively thinly bedded limestones of the Threadgill member of the Tanyard formation in the western part of the Llano region. Most of these are discontinuous, selectively dolomitized welts which average about as broad as the apertural diameter of the common snails of the same beds (Lytospira gyrocera, Ophileta polygyrata). They are restricted to the surface of the rock and thus are not borings. Commonly they seem to anastomose because of overlapping. Their discontinuous nature suggests that they were made by some buoyant benthonic organism that from time to time lost contact with the sea bottom due to surging of the waves. This, in connection with their size and their association with the common snails of the time (Pl.20, fig. D), strongly suggests that they are the trails of Lytospira and Ophileta.

The ancient snails, like the modern ones, doubtless secreted an agglutinating substance along the paths they followed, and this would serve to bind and localize the drifting coarser sediments of the time and encourage the selective dolomitization seen. The interruption of the trails suggests that they were made within reach of the surging action of the waves and probably indicates reasonably shallow waters.

At one place, in the same beds that display the common type of trail, a corrugated trail about one-third of an inch wide and 12 inches long was found. The nature of its origin is uncertain. Several broader bifurcating trails that occur in the same beds are also difficult to assign. They could have been made by cephalopods, resting suspended above but in contact with the sea-floor (as the squid Loligo does) and washing back and forth with the surging of the waves.

PROBABLE ECOGRAPHY AND OCEANOGRAPHY OF THE ELLENBURGER SEA

Evidence relating to the probable lithogeny of rocks of the Ellenburger group, the nature of Ellenburger life, and the relations of both to the environment of Ellenburger time has been presented above. This is now brought to bear on a summary of the probable oceanography and ecography of Ellenburger waters:

1. Ellenburger waters were marine. They supported many forms of life unknown except from marine environments and none that are known to be limited to fresh waters.

2. The Ellenburger part of the mid-Continent sea was shallow. Its bottom was surely less than 100 fathoms deep, probably at most times and places less than 15 and possibly less than 5 fathoms deep and perhaps locally awash. The environment was thus wholly neritic and possibly at times and places littoral, the terms neritic and littoral as here used referring to depth of water without implying any particular relationship to the principal shore areas.

   The intermittent presence of structures formed through the agency of algae (stromatolites) suggests a maximum possible depth of about 100 fathoms and their local development favors a depth of less than 15 fathoms (Cloud, 1942, p. 370-371). However, the depth of optimum photosynthesis was probably reduced by intermittent turbidity, resulting from the stirring up of calcium carbonate mud. Therefore, beds containing large and abundant stromatolites may have been deposited in waters considerably less than 15 fathoms deep. Black (1933b; see also Hatch, Rastall, and Black, 1938, p. 166) shows that colonies of sediment-binding algae that are now building structures comparable to the common stromatolites of the Ellenburger group actually have their optimun development in tidal flats, or above normal high tide, on near-shore flats that are periodically inundated by marine waters.

   Evidence that the sea bottom was affected by the surging action of waves is indicated by interrupted gastropod trails in the lower rocks of the Tanyard formation and by occasional development of ripple marks throughout the section. The local occurrence of polygonally cracked limestones suggests temporary subaerial exposure which may have occurred in mud-flats of

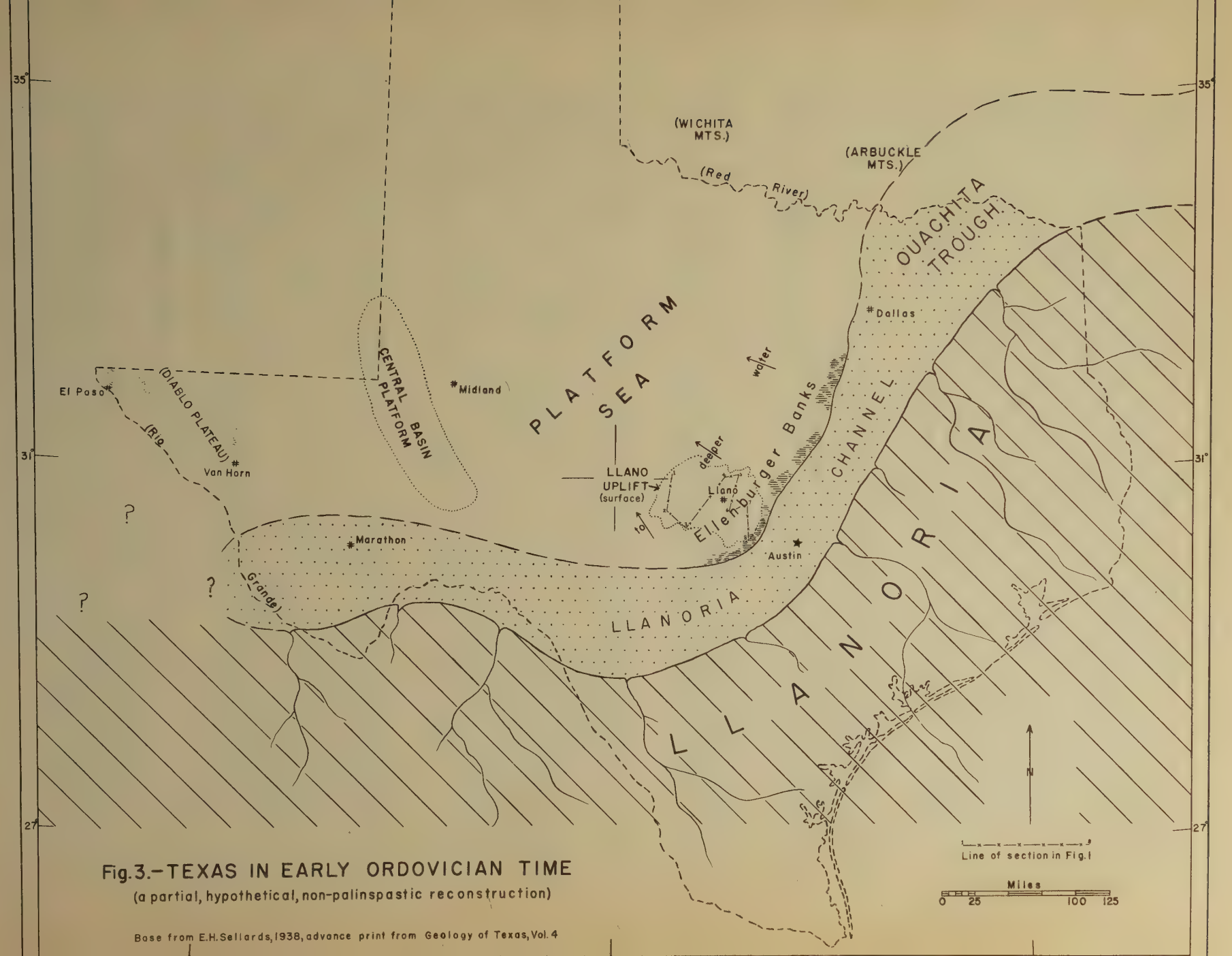

Fig.3.–TEXAS IN EARLY ORDOVICIAN TIME

(a partial, hypothetical, non-palinspastic reconstruction)

Base from E.H. Sellards, 1938, advance print from Geology of Texas, Vol. 4

the littoral zone between tides or even at higher levels. The local development of intraformational breccias or conglomerates, commonly in association with sands thought to be windborne, suggests waters sufficiently shallow to develop strong bottom turbulence during periods of storm. The great development of chemically precipitated carbonate muds from which the Ellenburger rocks were probably formed presupposes an environment of warm shallow waters; and the only known comparable sedimentary area in recent seas, the Bahama Banks, is mostly less than 3 fathoms deep and apparently does not exceed 5 fathoms in depth except on its shelving margins. If the temperatures of Ellenburger time were high enough and the circulation of the sea poor enough, the carbonate sediments might have settled undissolved through waters deeper than those in which flocculent carbonate minerals could survive in present seas.

Although it is not possible to place with surety an average depth shallower than the 15 fathoms thought to be required for optimum photosynthesis, and even though depths this shallow cannot be proved for beds in which stromatolites do not thrive, the data given above seem to substantiate the summary inference with which this section (2) began.

3. The water of the Ellenburger sea was warm, and probably so was the air above it. Tropical or semitropical conditions are strongly indicated by the great succession of chemically precipitated carbonate sediments from which the Ellenburger rocks were probably derived.

The evidences of primarily chemical deposition, and the general rarity of clastic fabrics suggest that the lime-muds of Ellenburger time may have been much more rapidly and abundantly precipitated than those of the Bahama Banks. This might suggest that the waters that moved into the Ellenburger part of the mid-Continent sea were more highly supersaturated with calcium salts, and that conditions affecting the precipitation of $CaCO_3$ were more persistent or more accelerated than they are over the Bahama Banks today. Of course, continuing or intermittent relative subsidence of sea bottom with respect to wave base is prerequisite for the accumulation of any sequence of shallow water sediments.

The known representatives of Ellenburger life do not furnish critical evidence on the temperature of waters of Ellenburger time. Although lime-secreting algae seem generally to grow better in warm water than in cold water, they actually have a wide thermal range and do not of themselves furnish direct information about the temperatures under which they lived (Cloud, 1942, p. 369-370). On the basis of numbers and variety alone, the Ellenburger fauna does not compare at all well with the war-water faunas of the present seas, except those found in unusual environmental circumstances such as occur on the Bahama Banks.

4. Ellenburger waters were probably well oxygenated.

Their dominant faunal elements are relatively large and thick-shelled gastropods and cephalopods. Intraformational conglomerates and breccias associated with probably wind-borne sands and the surging indicated by ripple marks and interrupted gastropod trails suggest intermittently turbulent conditions extending to the shallow sea floor.

5. The Ellenburger sea was intermittently turbulent and at such times was probably "milky" with flocculent lime-muds stirred up from the bottom.

   The opacity of the waters at such times doubtless inhibited the formation of structures dependent for their origin on phytosynthetic activity (stromatolites), and probably was unfavorable to the shell-bearing benthos and nekto-benthonic animals (shelled cephalopods) as well.

6. At most times and places the botton of the Ellenburger sea was soft.

   The patchy and intermittent occurrence of fossils in the Ellenburger group, except in the lower beds at the west side of the Llano region, suggests a generally soft bottom, inhibiting the development of the shell-bearing benthos except as the few places where firm bottom conditions prevailed. The probable nature of the original sediments comparable with those of the Bahama Banks suggests a similar conclusion.

7. The sea in which the lower sediments of the Tanyard formation accumulated probably had a firmer bottom on the west side of the Llano region than it did to the east.

   The abundance of large indigenous gastropods in the limestones of the Threadgill member of the Tanyard on the west side of the Llano uplift suggests this. The evidence of wave surging indicated by ripple marks and by interrupted gastropod trails shows that the water here was still fairly shallow, but that it was marginal to the areas of most active chemical sedimentation. This point is supported by the fact that the Tanyard formation is thinner on the western side of the Llano uplift than it is at the east.

8. In Ellenburger time land lay to the east and south of the Llano region. This land was either nearly level, relatively far removed, or separated from the Llano region by a channel. The sea floor was probably shallowest at the east and south sides of the Llano region and deepened gradually to the northwest (suggested in Figure 3 by the symbol for tidal flats just east of the surface expression of the present Llano uplift).

   Land to the east and south is indicated by the fact that the probably wind-borne sands of the post-Tanyard strata become more numerous and volumetrically more important to the east and south. That the land was either nearly flat, relatively far distant, or separated from the Llano region by a channelway (if not a combination of two or all three of these possibilities) is indicated by the absence from the Ellenburger of recognizable water-borne detritus. Deepening of the sea westward and northward is indicated by a general decrease in dolomite in this direction as shown on Figure 1. It has been noted that rocks that are dolomites in or towards the ancient shoal waters tend to grade seaward to limestone concomitantly with increase in depth and decrease in temperature of the bottom waters.

9. If the land that lay to the east and south of the Llano region was not nearer to the present margins of the Llano region in Gorman time than it was in Tanyard time and much of Honeycut time, then atmospheric turbulence was at its peak in Gorman time.

This assumption is based on the virtual absence of sand from the outcropping rocks of the Tanyard formation and the fact that it is commoner and more abundant in the Gorman formation than in the Honeycut. In the southeastern part of the region (Johnson City area) evidence of marine (and atmospheric) turbulence was observed by Barnes to be commoner in the Gorman formation than in the beds above and below it. Evidence on this point from other parts of the Llano uplift is less certain, but either it is in support of (e. g., Lake Victor quarry) or at least not in conflict with observations from the southeastern part of the region.

10. The Ellenburger sea varied in depth, temperature, and chemical environment, both geographically and in time.

Inasmuch as dolomitization is probably favored not only by chemical factors but by elevated temperatures, and because water temperatures ordinarily decrease with depth, penecontemporaneous dolomites may indicate shallower, warmer waters at the time of their formation than do limestones. The later diagenetic dolomites suggest inception of conditions favoring dolomitization somewhat after deposition and at least partial compaction of their source sediments. Probably every gradation between penecontemporaneous and late diagenetic dolomites exists. The geologic evidence suggests that coarseness of grain is related to slowness and irregularity of dolomitization, which in turn is related to permeability, or degree of compaction, and hence to the thickness of sediments above those being dolomitized. The coarser the grain, therefore, the later in diagenesis did dolomitization probably occur, and the greater was the lag between deposition of the source sediments and inception of the chemical and temperature conditions that favor dolomitization.

Lateral irregularity of dolomitization is doubtless in part controlled by the relative permeability of the sediments, and by the mineralogic character of the carbonate sediments being transformed. The metastable mineral aragonite, for instance, is more readily dolomitized than the stable mineral calcite. Variations in permeability and mineral composition of the original sediments are not only themselves suggested by irregular dolomitization, but they are in turn probably responsible for the conditions whereby one may infer roughly the stage in diagenesis at which dolomitization occurred.

Application of the above suggestions to the distribution of dolomites shown in Figure 1 will indicate to the reader in a general way where and when the seas of Ellenburger time in the Llano region may have attained their highest temperatures and shallowest depths, and Figure 3 will aid visualization of inferred paleogeographic relationships. A feature to be noted on Figure 1 is the thinly alternating sequence of limestones and dolomites that characterizes the lower part of the Honeycut formation. These suggest the inception of fluctuating disequilibrium in the sea after a long period of relative stability of relationships in late Gorman time.

This condition of instability may have taken the form of simple fluctuations in depth and temperature. It may equally well have been related to more complex conditions related to the physical chemistry of sea water

and favoring penecontemporaneous (or primary ?) dolomitization through the rythmic depletion in $CaCO_3$ of successively invading currents supersaturated with dissociated potential compounds of both calcium and magnesium, and with an excess of the CO_3^{--} ion. In any event variations in temperature and depth probably had some effect on the dolomitization process, in the direction indicated.

It should be mentioned that A. E. Parr (oral communication to Cloud, Nov. 1, 1938) has described how inclosed saline waters under certain conditions may be flooded and covered with fresh waters from the land and heated up much in the manner that the air in a greenhouse is warmed by the sun. According to Parr, data from one such inclosed area on the coast of Norway showed a temperature of 16° C. higher at 2 meters below the surface than at the surface, and at some places along the coast of Norway the growth of oysters is fostered by such "hothouse effects."

Although it is not suggested that this applies to the dolomites of the Ellenburger group, periodic repetition of some such mechanism acting on sluggish waters could explain rythmic dolomitization as well as could variations in depth of water alone. But again, shallowness of water would probably facilitate the process, and the prolonged overspread of a freshwater cover on shallow saline waters could produce optimum conditions for elevated temperatures and penecontemporaneous or later diagenetic dolomitization provided mixing did not occur.

11 Although variations in the general types of life that dwelt in the Ellenburger sea are not marked, stratigraphically significant faunal variations in the Ellenburger rocks are apparent. The stratigraphically significant faunal changes that can be correlated with similar changes in distant regions are held to be most logically related to eustatic or epeirogenic movements.

At most places fossils are markedly more abundant in the Tanyard and Honeycut formations than they are in the Gorman formation. The most conspicuous difference in general faunal aspect is the relative abundance of sponges and trilobites and the dominance of heavily operculated gastropods (Ceratopea) in the Honeycut formation.

Quite apart from the broad faunal similarities, there are stratigraphically marked faunal changes at the Tanyard-Gorman and Gorman Honeycut boundaries, and these correlate with faunal changes that are widespread in North America. They, therefore, must mark widespread phenomena. Eustatic fluctuations, (changes in the volume of the oceans, or movements of the ocean bottom itself, affecting the volume of water on the continents and the depth of water in entire epicontinental seas) seem to us to be a more logical vehicle for accomplishing such widespread changes than do hypotheses relating to barriers or other factors equally logical for changes of lesser extent.

Epeirogenic movements of the proper scope could produce similar results. Shrinking of the epeiric seas, whether related to eustatic changes or epeirogeny, doubtless affected climatic conditions; and this, plus concomitant changes in depth and salinity, could affect extermination of the

faunas from the regions occupied by shallow seas without requiring prolonged subaerial exposure, and perhaps without subaerial exposure at all. Repopulation would follow marine reinvasion, and if environmental conditions were similar to those previously existing, faunas of generally similar but taxonomically different aspect should result. Other factors capable of producing results so widespread (e. g., climatic, changes in chemical environment, eruptive mass evolution) would doubtless themselves relate to changes of some broad nature such as might logically be attributed to eustatic or epeirogenic causes.

In the Llano region, the Ellenburger sea was probably so shallow that the region was actually exposed to the atmosphere at the time of marine recessions, that is, at the Tanyard-Gorman and Gorman-Honeycut boundaries. Perceptible truncation was not accomplished because atmospheric agencies were not adequate to affect the wide low-lying mud-flats, and because the waters of the shallow reinvading epeiric sea were probably sluggish except at times of strong atmospheric disturbance.

12. Although conditions in general during Ellenburger time were not favorable to the shell-bearing bottom-dwellers, there were probably at most times local areas where benthonic and nekto-benthonic shells could and did survive. At some times favorable conditions were more widespread in the region and relatively abundant broadly endemic shelly life developed, but it is believed that in most instances this was an outgrowth from forms that held on through the unfavorable periods. Analogy with conditions on the Bahama Banks suggests that survival was in large part related to firmness of the bottom.

13. Even though shell-bearing animals may have been rare during much of Ellenburger time, the abundant presence of soft-bodied organisms is indicated by the abundance of pelleted areas in the limestones (Moore, 1933, 1939). This bears directly on the potentialities of the carbonate rocks of the Ellenburger group as source sediments of petroleum.

The almost self-evident conclusion that "the more organic matter a recent marine deposit contains the greater are its chances of being a potential future source of petroleum" was reaffirmed by Trask as a result of extensive studies by himself, Hammar, and Wu (1932, p. 239). In view of the probably extensive mud-ingesting fauna of the Ellenburger strata, it is no longer safe to regard these strata as an unlikely source of petroleum where they are not in a position to receive leakage from above.

14. The only known area of recent sediments that can be compared closely with those from which the Ellenburger rocks were theoretically derived is the Bahama Bank region. If the Llanoria channel of the Ouachita trough (see Sellard, 1931, 1932; Miser, 1934; DeFord and others, 1940) extended to the east and south of the Llano region as early as the beginning of Ordovician time (as suggested in Figure 3), the Ellenburger sediments may actually have been separated from the mainland of Llanoria by a relatively deep channel.

If the "Ellenburger Bank" was as near the sea surface as we think, a channel 60 to 100 fathoms deep would have been "relatively deep," or it could

have been deeper. Under the postulate diagrammed in Figure 3, the Llano region of Early Ordovician time is visualized as a submarine bank, deepening gradually to the west, and with shoals and perhaps tidal flats or even local island areas lying at the south and east margins as Andros Island lies between the western lobe of Great Bahama Bank and the tongue of the ocean (Fig. 2).

Whatever happened at the south and east, it is doubtful if the sea bottom dropped off steeply to the west and north, or to great depths on any side. That the Llano region could have been a structural as well as a sedimentational counterpart of the Bahama Banks in Ellenburger time is suggested by its positive structural history, and the known sedimentary evidence from the surface and from the subsurface to the north reveals no features in this direction that could be interpreted as the margins of an abrupt bank. However, thinning of the sediments and an increasing proportion of limestone along the west side of the southern end of the Bend arch that extends northward from the Llano uplift suggest that there may have been a westward steepening in pitch of the bottom profile essentially coincident with the crest of the present-day Bend arch.

Reservations must be made in speculating about what actually lay immediately adjacent to the Llano region at the south and east. Were the Llanoria channel of the Ouachita trough not a well-documented feature of later times, and were it not indicated to be so suggestively like the narrow channels that separate the Bahama Banks from Florida and Cuba, (fig. 2) we might have guessed that the Ellenburger sea graded directly to a peneplained hinterland in these directions. Even a flat and distant hinterland, however, does not explain the remarkable scarcity of terrigenous debris in the Ellenburger rocks as well as a current swept channel separating the Ellenburger shoals on the north and west from land on the south and east.

COMPARISON OF THE ELLENBURGER SEA WITH OTHER ANCIENT MARINE PROVINCES

Late Cambrian seas of central Texas

Paleogeographic maps of Late Cambrian and Early Ordovician time (Schuchert, in Schuchert, and Dunbar, 1941, figs. 70, 84) show the epicontinental seas and channel ways of those two times to have had very similar patterns. It seems unlikely that Schuchert's "Ouachita trough" extended west as far as it is shown in Late Cambrian time, but in central Texas the general position of the shore lines was probably close to that shown by Schuchert.

Our principal interest lies in evidence that may bear inferentially on actual differences between the environment of the Cambrian waters and that of the later Ellenburger sea. In contrast to those of the Ellenburger, the Upper Cambrian faunas are dominated by trilobites, with brachiopods locally abundant and with gastropods rare except at places in the higher carbonate rocks. In general, however, the Upper Cambrian faunas are larger and more varied than those of the Ellenburger, and evidences of organic activity in the form of pelleting and burrowing of the sediments are more widely common in the generally detrital limestones of the Cambrian than in the chemically precipitated limestones of

the Ellenburger or certain of the latest Cambrian sediments. The Cambrian rocks are dominated by detrital limestone, sandstone, and shale. Stromatolitic limestones are locally well developed, and the upper carbonate rocks are generally finer grained and more typically dolomitic in the eastern part of the Llano uplift than in the west (due to unconformity, special conditions obtain in the southeastern corner of the uplift). The stromatolitic limestones are commonly microgranular to sublithographic, and ordinary limestones of the San Saba limestone member of the Wilberns formation are not uncommonly sublithographic in the more easterly exposures. Glauconite occurs abundantly to sporadically in the granular limestones of the Upper Cambrian strata; but macroscopically visible glauconite is apt to be absent or much reduced in quantity in the microgranular to sublithographic limestones, the noncalcareous sandstones, and the shales.

Application to these facts of the inferences that have been made on previous pages results in the conclusion that the environment of the late Cambrian seas differed from that of the Ellenburger sea in several important respects.

Of course the fossils and the presence of glauconite show that the Cambrian sea was definitely saline, except possibly during the first part of the interval when the Hickory sandstone member of the Riley formation was being deposited. The general presence of glauconite suggests that, for the most part, the bottom of the sea in which the Upper Cambrian sediments accumulated was deeper, and perhaps colder and less well oxygenated than that in which the Ellenburger strata were formed. The first two inferences would seem to be supported by the rarity of dolomite and of chemically precipitated limestones except locally and in the highest Cambrian strata. If the inferences of Galliher (1935a, 1935b, 1937) are valid, glauconite in the Cambrian strata also suggests the presence of igneous or micaceous metamorphic rocks on nearby coasts or islands. Such islands, incidentally, are known (Bridge, Barnes, and Cloud, 1947, p. 113) to have been present at least as late as the Cap Mountain time of deposition of the limestone member of the Riley formation. The continued or intermittent presence of a large island or other land mass directly west of the Llano region, almost if not quite to the end of Cambrian time, is indicated by the locally thick water-borne sands of the San Saba limestone member of the Wilberns formation in the western areas (Fig. 1; Cloud and Barnes, 1948, p. 156, 179-182, 344). The waters adjacent to this land mass were probably deeper than those to the east, except in later but not latest Wilberns time when dolomitization of the calcareous sediments was there locally occurring.

That the waters of the Late Cambrian sea were intermittently shallow and probably warmer after the deposition of the Morgan Creek limestone member of the Wilberns formation is indicated by the intermittent occurrence of prominent stromatolitic bioherms and biostromes. The highest Cambrian strata as they are traced eastward show a rising proportion of sublithographic, sparingly glauconitic to non-glauconitic limestones. This suggestion of increasing chemical precipitation combines with the increased dolomitization eastward to indicate that the principal shoal area of the times, at least of latest Cambrian time, lay to the east of the present Llano region. A general shoaling of the Cambrian seas toward the end of Cambrian time is suggested. The eastern part of the Llano region was above wave base, and possibly above water, for a long enough time at the end of the Cambrian to permit considerable truncation of

Cambrian sediments in the southeastern part of the region (see position of Plectotrophia zone in fig. 1) and lesser truncation elsewhere (Cloud and Barnes, 1948, Pl. 20, fig. A-B). In the western part of the region sedimentation was probably continuous across the Cambrian-Ordovician boundary (Cloud and Barnes, 1948, Pl. 19, fig. D) and eustatic effects or minor epeirogenic deleveling, with subsequent environmental changes, may be called upon to explain the faunal break at this place.

Coeval provinces of the mid-Continent sea

Of the equivalent outcropping Lower Ordovician rocks of the mid-Continent region, those of the Ozark uplift most nearly resemble the Ellenburger strata in faunal aspects, types and volume of chert, and probable lithogeny. Even these, however, differ from the Ellenburger in the fact that they are almost wholly dolomitic, and especially in the large amount of terrigenous material that is to be found in many of them (Cullison, 1945). In fact, no sequence of Lower Ordovician rocks known to the writers is so persistently low in materials of terrigenous derivation as is the Ellenburger group. The upper part of the Gasconade dolomite in the Lower Ordovician of the Ozark region and, in places, the Newala limestone of the Appalachian region make the nearest approach to it.

In the Arbuckle and Wichita mountains the rocks equivalent to the Ellenburger group of Texas are much thicker, contain much terrigenous materials, and are almost wholly calcitic. Those of the Marathon basin are thinner, contain much terrigenous material, and consist of limestones with interbedded shales, and slightly dolomitic beds (Monument Spring "dolomite" member of the Marathon limestone) near the middle. Those of the Sierra Diablo, Franklin Mountains, and the Rocky Mountain Front all differ in their content of terrigenous material and in other features described by us elsewhere (1948, Part 3), those of the southeastern part of the Sierra Diablo region being most similar to the Ellenburger.

To forestall confusion in the ensuing resume, attention is invited to the fact that relative thickness of sediments in itself bears no necessary relation to the depths of the waters in which they accumulated. It is a matter of common knowledge that to accumulate a thick series of sediments in shallow waters requires progressive relative depression of the sea floor; but that actual thicknesses of sediments accumulated, granting an adequate receptacle for them (e. g., a subsiding basin), depends on the source of supply and the competency of the transporting agents.

Bridge (1930, p. 156) considered the sediments of the Ozark area of the mid-Continent sea to have been "quite similar to the lime sediments now accumulating on the Great Bahama Bank." Cullison, in his summary of conditions in the Ozark region (1945, p. 52), "believed that the lower Ordovician sediments were deposited in seas which were commonly muddy, shallow, and hypersaline." He points out (Cullison, 1945) that the faunas are found in zones between which are appreciable thicknesses of unfossiliferous dolomite; and he infers that this is to be explained by successive faunal invasions induced by better marine circulation and decrease of detritus, "due perhaps to eustatic changes." Schuchert (in Schuchert and Dunbar, 1941, fig. 54) shows that the Ozark region proper lay far from land almost in the middle of a great epicontinental sea.

On a structural basis, therefore, the Ozark region of early Ordovician time may have been similar to the Bahama Banks except in degree of submarine relief. However, in some manner terrigenous materials were much more abundantly supplied to it, and from a sedimentational point of view the Ellenburger area more nearly resembled the Bahama region. Bridge (1930, p. 138-147) shows that portions of the Ozark uplift were emergent at various times during the deposition of the Lower Ordovician sediments, and these emergent areas doubtless furnished the detrital material. The fact that in the Ozark region the carbonate rocks equivalent to the Ellenburger are all dolomitic suggests that the sea waters retained more uniformly elevated temperatures and shallower depths than did those of the Ellenburger area. These observations are in line with the descriptions and most of the inferences made by Cullison (1945). We question, however, the advisability of invoking eustatic changes to account for the successive faunal invasions noted by Cullison (1945). If these were related to movements of the ocean bottom or to changes in the total volume of water in the oceans, that fact should be reflected by correlative features in other regions, and only those faunal changes which are so reflected should be explained by other than local mechanisms.

Along the Rocky Mountain Front the Manitou formation at places overlaps the so-called Sawatch quartzite (Cambrian) and pinches out against the pre-Cambrian rocks. The shore line was evidently irregular and the carbonate sediments were deposited in varying depths of water receiving varying and commonly large quantities of fine detritus. In the sections examined by us the Manitou is dolomite where it rests directly on pre-Cambrian and largely limestone where the so-called Sawatch intervenes, a situation indicative of the relation between dolomitization and depth of water.

In the region of the Diablo Plateau and the Franklin Mountains of west Texas (Cloud and Barnes, 1948, Pl. 16) the earliest established invasion of the Paleozoic seas occurred in Lower Ordovician time when the Tanyard formation was deposited. The Bliss sandstone at the type locality in the Franklin Mountains can not be correlated directly with the Tanyard formation, but only by analogy with the so-called Bliss sandstone of the Sierra Diablo. The upper part of the latter is known to be of Tanyard age, the former has always been considered and may yet prove to be Cambrian. In any event, the sea of Tanyard time in the Sierra Diablo region, and probably in the vicinity of the present Hueco and Franklin Mountains received copious quantities of quartz-sand. The shore was thus nearby and probably of relatively marked relief. The depth and temperature of the sea are more highly speculative matters to which the interested reader may apply the ecologic inferences suggested earlier. The sea of Gorman time received much water-borne sand in the Sierra Diablo region and considerably less in the vicinity of the Franklin Mountains. At the former locality, therefore, it was either nearer land or adjacent to land of more marked relief or more deeply mantled with clastic debris than at the latter. Reasonably warm temperatures and shallow depths for the sea of Gorman time are suggested by the relatively common dolomitization of rocks of Gorman age in both the Sierra Diablo and the Franklin Mountains (Cloud and Barnes, 1948, Pl. 16). Strata of Honeycut age are largely dolomite at the southeast corner of the Sierra Diablo region (Beach Mountain section) and largely limestone between there and the Franklin Mountains. Terrigenous materials are relatively uncommon throughout rocks equivalent to the Honeycut formation, being represented by minor silt and

argillaceous material and rarely by sand. The sea of Honeycut time thus may have been warmer and shallower at the southeast corner of the Sierra Diablo region than it was northwest from there, but the land to the south was furnishing little terrigenous debris. The implications of the post-Honeycut strata are not pertinent to this discussion.

The Marathon limestone, which is partially equivalent to the Ellenburger group, consists of flaggy argillaceous limestone "with much interbedded shale and occasional layers of conglomerate and sandstone" (King, 1937, p. 27). Fossils are uncommon, and at most places the fauna is dominated by graptolites. Near its middle is a thin zone of thickly bedded siliceous and in minor part dolomitic limestone, more nearly resembling the Ellenburger than other rocks in the sequence, and containing cephalopods, gastropods, and articulate brachiopods. Conditions markedly different from those of the Llano region are indicated for the Early Ordovician sea of the Marathon basin and the Big Bend in Trans-Pecos, Texas. The general absence of dolomite suggests that the Marathon limestone accumulated in relatively deeper, cooler waters than did the equivalent sediments of the Llano region. Much fine argillaceous material and organic matter was contributed to the limestones. It discolored them and locally made shale beds. The limestones are commonly sublithographic, suggesting that they may be the undissolved remnants of chemically precipitated calcium carbonate that drifted into the region and mixed with the argillaceous matter. Although deep and cool in comparison with the Early Ordovician sea of the Llano region, neither excessive depths nor truly low temperatures are indicated. Stromatolites in the siliceous limestone near the middle of the Marathon limestone indicate temporarily shallow waters. According to our concepts, as previously stated, mere thickness of sediments bears no finite relationship to depths of the waters in which they accumulated. Thus it is not sound to conclude as has been done (Barton, 1945) that the thinness of the Marathon limestone bars it from admission to the category of trough (or geosynclinal) sediments.

The Lower Ordovician rocks of the Arbuckle and Wichita Mountains are largely limestones that are dark in color from contained argillaceous material and that locally are arenaceous. They are much thicker than equivalent carbonate rocks in other parts of the mid-Continent. The absence of dolomite suggests that they accumulated in deeper, cooler waters than those of the Llano region. However, the intermittent occurrence of stromatolitic structures indicates that the waters were nevertheless relatively shallow much of the time, and much of the limestone may have been chemically precipitated. The relation of these rocks to the well-known belt of clastic rocks in the Ouachita area (Miser, 1934) indicates that, whereas the province of the sea wherein their sediments accumulated lay to the northwest of the Ouachita trough, the distinction between trough and shelf was not as great as it was farther to the south, and subsidiary currents were enabled to carry to the Arbuckle-Wichita province such clastic sediments as they were competent to handle.

The Early Ordovician sea of the southern mid-Continent is seen to have been a great epeiric sea with a variety of shore line features, shoals, islands (see also Walters, 1946), and channels. It is doubtful if at any place or time its depth greatly exceeded 100 fathoms, and extensive banks and offshore flats of carbonate muds were probably at times awash. At the same time, progressive

subsidence is called for to permit the accumulation of the sediments. The principal channel way of the larger region here considered was the Ouachita trough, which, with its subsidary Llanoria channel, appears to have lain between land to the southeast and shoal waters to the northwest. The Llanoria channel probably extended as far southwest as the Big Bend province of Texas, but whether it extended beyond, ended as a cul-de-sac like the tongue of the ocean in the Bahaman region (Figs. 2, 3), or simply faded out is not known. Presumably the Llanoria channel was narrower, and the recipient of less and mostly finer sediment than was the Ouachita trough proper. Thus the lands that bounded it to the east and south may have been lower, and the clastic sediments largely current-borne from the northeast. The boundary between it and the dominantly shoaly banks to the west and north may have been in part at least fairly well defined, and the relative thicknesses and nature of sediments accumulated are to be taken as representative of volume of supply and rate of subsidence.

FACIES OF THE LOWER ORDOVICIAN ROCKS AND THEIR PALEOECOLOGIC IMPLICATIONS

It is of interest that the known nonquartzose Lower Ordovician rocks of the United States fall in or adjacent to three broad faunal and lithologic facies. For purposes of preliminary discussion these may be called (1) the shale-graptolite facies, (2) the limestone-brachiopod facies, and (3) the cherty carbonate-molluscan facies, although it is simpler to use faunal designations only. We suppose that the order of their naming parallels the order of decreasing depth of the waters in which they formed, and we recognize gradations between 1 and 2 as between 2 and 3. The distinction between the limestone-brachiopod facies and the cherty carbonate-molluscan facies is one that we have previously recognized in thought but not in discussion, grouping the two together as "The carbonate facies of the Lower Ordovician." Such a grouping is properly maintained for general discussion, but the subdivision is of value in paleoecologic considerations.

(1) The shale-graptolite facies is exemplified by the well-known black Deepkill shale of the Eastern States, but it has counterparts in the clastic facies in the Ouachita area and probably in the subsurface of the Llanoria channel (as well records indicate). We consider the interbedded, graptolite-bearing, black flaggy argillaceous limestones and somewhat fissile shales of the Marathon limestone to represent a marginal aspect of this facies, gradational toward the limestone-brachiopod facies. The shale-graptolite facies is thought to be characteristically a deposit of troughs or channels, laid down in relatively deep waters but probably not far from shore and not necessarily to great thicknesses. Where this facies is not interbedded with coarse siliceous detritus, the adjacent lands were probably low, and distribution of sediments may have been to a large extent controlled by long-shore currents within the channels. The capacity and spread of the currents and the available supply of material at the source probably had important bearing on the thickness of accumulation of the shale-graptolite facies and on the degree of contamination with such detritus of carbonate sediments being formed in adjacent waters.

(2) The limestone-brachiopod facies is repressnted by commonly dark and somewhat argillaceous and otherwise impure limestones that have occasional interbeds of calcareous shale but are nevertheless predominantly high-calcium

rocks and are rarely more than slightly dolomitic and cherty. Faunally such rocks in the Lower Ordovician are characterized by a relative abundance and variety of brachiopods although graptolites are not uncommon in them and molluscan faunas are locally abundant. In fact, the fauna is better balanced than in either of the other two facies. This facies is exemplified by the Lower Ordovician rocks of the Arbuckle group in Oklahoma, by the upper part of the El Paso formation of the Franklin and Hueco Mountains in West Texas, and by a good part of the Lower Ordovician rocks of the Great Basin region. In the instance of the Arbuckle section, the limestone-brachiopod facies is a largely detrital high-calcium rock that is contaminated by siliceous clastics probably washed in from the Ouachita trough proper. In this region the Ouachita trough was probably broad, well supplied with clastics, swept by competent currents, and not sharply separated from the platform sea in which the Lower Ordovician rocks of the Arbuckle group were accumulating. The latter were thus widely contaminated with terrestrially derived detritus and the calcium-carbonate sediments widely reworked, resulting in clastic textures. The platform sea was probably relatively shallow, but not shallow enough over long enough intervals for dolomitization to be common or for the shallow-water molluscan faunas to reach the dominance they attain in the cherty carbonate-molluscan facies.

(3) The cherty carbonate-molluscan facies includes the rocks of the Ellenburger group, the Lower Ordovician rocks of the Ozark dome, and a large part of the Lower Ordovician carbonate rocks in the Appalachians. Rocks assignable to this facies probably represent the diagenetically dolomitized calcareous deposits of shallow warm waters in which gastropods and cephalopods were the favored shell-bearing faunal elements. It is significant that dominance of these faunal elements in the Lower Ordovician is so commonly associated with the fact that the rocks in which they occur are intermittently or continuously dolomitic, markedly cherty at many levels, and that such interbedded limestones as occur have commonly the characteristics of lithified chemical precipitates. It seems almost as though the molluscs had the upper hand in available ecologic niches for most of the time, and that the brachiopods that occur in these rocks got along more or less by sufferance, as it were. The possible variables to be considered in speculating about this situation include depth, temperature, chemical composition, and oxygenation of the water; turbidity resulting from stirring up of flocculent bottom muds; firmness of bottom; and other factors. Information available does not warrant an extensive survey of the more abstruse possibilities, but it is certainly significant that the favored organisms were vagrant benthos (gastropods), those few cephalopods with subterminal apertures or nekto-benthonic to weakly nektonic animals (other cephalopods). These animals would have been able to dig out or migrate when overwhelmed by encroaching muds such as would have smothered adults of sessile benthon such as brachiopods, and the latter would have been able to survive only in reasonably permanent areas of firm bottom.

The carbonate rocks that are dolomitic but not markedly cherty, such as the El Paso formation of the Sierra Diablo region and the lower part of the same formation in the Franklin Mountains (both in West Texas) are more or less intermediate in lithologic and faunal characteristics between the cherty carbonate-molluscan facies and the limestone-brachiopod facies.

Why chert is characteristically associated with the development of a molluscan fauna in the Lower Ordovician is a problem. Apparently much of this chert

is syngenetic and formed under widely occurring conditions of generally contemporaneous environmental similarity, an inference suggested by the usefulness (with caution) of types of chert in correlation of the Lower Ordovician rocks. Seemingly factors at least generally related to those that favored dolomitization and the dominance of a molluscan faunal facies also favored the development of broadly correlative types of syngenetic chert.

RESUMÉ OF EARLY PALEOZOIC EVENTS

The first Paleozoic sea to invade Central Texas entered a region of considerable relief. The invasion occurred at about the same time as the initial invasion of the Ozark uplift (Bridge, 1937, Table I) and encountered a similar topographic situation. (Bridge, 1930, p. 136-139). It reworked sands of eolian origin (Barnes and Parkinson, 1940) into the base of the Hickory sandstone member of the Riley formation, but whether a part of the Hickory actually represents eolian sedimentation is not known. To be sure, it is essentially nonglauconitic, in contrast to the higher Cambrian strata, but Hadding (1932) has shown that the true, primary basal beds in the marine series of strata are typically nonglauconitic. Hills several hundred feet high projected above the initial sea floor, and some buried hills are known to extend stratigraphically into the Cap Mountain limestone member of the Riley formation (Bridge, Barnes, and Cloud, 1947, p. 113).

The lands were largely denuded of quartzose detritus or reduced in elevation by the middle of Riley time and the Cap Mountain limestone member of the Riley formation is composed of granular, essentially detrital, glauconitic limestones. These are locally trilobite shell-breccias and probably originated in a not excessively shallow and perhaps a relatively cool neritic environment, wherein there dwelt numerous trilobites as well as soft-bodied organisms whose only traces are their faecal pellets. The abundance of organic remains possibly was instrumental in effecting the large potash return suggested by the abundance of glauconite in the sediments. During the changes in relationship of land to sea that occurred in late Riley and early Wilberns time, the lands again supplied abundant sand to compose the regressive-transgressive sand zone in the midst of which the Riley-Wilberns formational boundary is drawn.

The Welge sandstone member of the Wilberns formation includes minor detrital glauconite and grades upward into reddish and locally earthy granular limestones at the base of the glauconitic Morgan Creek limestone member. Detritus of terrestrial origin decreases upwards and the granular limestones of the Morgan Creek limestone member suggest, like those of the Cap Mountain limestone deposited in later Riley time, a not excessively shallow and perhaps relatively cool neritic environment. During middle Wilberns time quantities of argillaceous material were contributed to the sea from a westward direction to comprise the Point Peak shale member. This shale is displaced by dolomitized and rather pure carbonate rocks to the east, indicating that in that direction lay warm shoal waters barred or far removed from an effective source of terrigenous debris. The transposition of the San Saba limestone member into the Pedernales dolomite member eastward indicates that these easterly shoals were persistent to the end of Wilberns time. The continued or intermittent presence of a large island or other land mass to the west, almost if not quite to the end of Cambrian time, is indicated by (a) the locally thick water-borne sands of the

San Saba limestone member of the Wilberns formation in the western part of the region (Fig. 1; Bridge et al., 1947, p. 120-121; Cloud and Barnes, 1948, p. 156, 179, 344), and (b) the decrease toward the eastern margin of the Llano uplift in the amount of terrigenous detritus representing the Point Peak shale member of the Wilberns (Fig. 1; Bridge et al., 1947, Pl. 1, p. 116). Occasional local shoaling in the vicinity of this land is suggested by the abnormal occurrence of dolomite typical of the Pedernales 130 feet below the top of the Wilberns formation in the northwestern corner of the uplift (Bridge, et al., 1947, Pl.1, section 1; Cloud and Barnes, 1948, p. 345).

Intermittent shoaling and warming of the waters in which the post-Morgan Creek sediments were deposited is indicated by the local conspicuous development of stromatolitic limestones. The increasing proportion of sublithographic limestone and dolomite eastward in latest Cambrian time indicates a general shoaling of the region in that direction. The sea floor sloped to the northwest, and either depression of sea level or tilting in a northwesterly direction resulted in emergence of the southeastern part of the Llano region and truncation of highest Cambrian strata (see position of Plectotrophia zone in Fig. 1). Marine conditions probably persisted to the west, with sedimentation being continuous across the Cambrian-Ordovician boundary (Cloud and Barnes, 1948, Pl. 19, fig. D).

At the beginning of Ordovician time either the Ouachita trough was in existence, or the hinterland to the south and east had been reduced to a peneplain--perhaps both. Any islands that might have contributed terrigenous sediments were buried, and the floor of the shallow, tropical or subtropical sea sloped gently to the northwest, away from shoals at the south and east. The region was repopulated with a dominantly molluscan fauna, unlike the dominantly arthropodan fauna of the Cambrian.

During Early Ordovician time the Llano region remained relatively stable, with minor fluctuations in depth and temperature of water, condition of the bottom, and nearness of land. The marine waters of the region were primarily warm, intermittently turbulent, and relatively well oxygenated shoal waters, deepening to the northwest. Sedimentationally and ecologically the region was like the Bahama Banks off the southeast coast of Florida. Its generally soft bottom of pure carbonate muds and the intermittently muddy nature of its waters inhibited the development of shell-bearing bottom dwellers except in local areas where firm bottom conditions occurred. Where and when favorable bottom conditions prevailed, these local colonies were enabled to coalesce and extend more widely through the region. The faunal changes at the formational boundaries correlate with similar faunal changes in other regions and probably are related to eustatic or epeirogenic movements. Equilibrium conditions (thermal, depth, chemical) of the ancient waters at any particular time are suggested by the character, persistence, and frequency of penecontemporaneous dolomitization.

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ECOLOGY OF LIVING NAUTILOIDS

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Data obtained from the study of living species of Nautilus have considerable meaning in the biologic interpretation of fossil nautiloids and ammonoids. From the point of view of the paleontologist, studies of living Nautilus are greatly to be desired, and it is unfortunate that so little is known about this animal.

The following notes are culled from several, mostly minor publications and pertain to the biology of living Nautilus. Unpublished observations by Dr. Curt Teichert of the University of Melbourne are also included. The writer wishes to thank Dr. Teichert for his kind help in gathering information on Nautilus.

Geographic Distribution

Living Nautilus is restricted to the southwest Pacific. Its geographic range is from South Australia (this is a significant extension of the previously known range, see Riddle, 1920) on the southwest to the southern Philippine Islands, Negros and Cebu, on the north and eastward to the Fiji Islands. It does not occur farther east in the Samoan Islands (Bennett, 1859). The center of distribution is in the group of islands from New Caledonia and the Loyalty group northwestward to New Guinea and the Bismarck Archipelago. There are no records of living Nautilus from New Zealand. A list of records for live specimens follows:

(1) Foul Bay, Southern York Peninsula, Australia, Nautilus pompilius Linné, alive; collected in 1911 and published by Riddle 1920. Tom Iredale 1944 rejected this report without stating his reasons for doing so. However, Verco & Cotton 1928 and Cotton & Godfrey 1940 accepted it. Dr. B. C. Cotton still accepts Riddle's reports as authentic and Dr. Curt Teichert states that the original report leaves no doubt whatsoever that the animal was a live one (letter dated September 15, 1948).

(2) Islands of the Eastern Archipelago, Eromanga, Ancityum, and other islands of the New Hebrides and also the Fiji group; N. pompilius Linné. (Bennett 1859)

(3) Isle of Pines and New Caledonia; very plentiful at Ware (Mare?), an island about 30 miles from New Caledonia; N. macromphalus. (Bennett 1859)

(4) Solomon Archipelago, New Georgia, New Britain, New Ireland, and probably to the eastward of these groups of islands, N. umbilicatus. (Bennett 1859)

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(5) Nautilus not found at the Navigator (Samoa) group of islands. (Bennett 1859)

(6) New Britain in the Bismarck Archipelago, N. pompilius. (Willey 1898 & 1899)

(7) Off East Cape of British New Guinea, N. umbilicatus. (Willey 1899)

(8) Sandal Bay, Lifee or Lifu in the Loyalty Group, N. macromphalus. This species is said to be confined rigidly to New Caledonian Archipelago. (Willey 1898 & 1899)

(9) New Hebrides and Fiji, N. pompilius Linné. (Willey 1899)

(10) Marachini Bay in the southwest side of island of Eromanga, one of the New Hebrides, taken in 1831 by Bennett and dissected by Owen, N. pompilius Linné. (Edwards 1849)

(11) Off southern coast of Negros, Philippine Islands, 66 specimens, N. pompilius Linné. (Griffin 1900)

(12) Straits between the islands of Negros and Cebu and off the southern coast of Siquijor, Philippine Islands; also stated to be doubtless common throughout the waters of the southern Philippines; N. pompilius Linné. (Dean 1901)

(13) Off Matuku, Fiji Islands, 315 fathoms, coral mud, living N. pompilius (Hoyle 1886); living specimen also reported from Kandavu, Fiji Islands.

Dead shells of Nautilus float far from the area where it lives. They are recorded from as far north as Japan apparently carried along by the Kuro Siwo surface current. One shell was picked up at the beach at Misaki, Japan, latitude 35°10' North (Dean 1901). Shells of N. pompilius and N. macromphalus not infrequently wash ashore on the Ninety-mile Beach on New Zealand (Powell 1946). Angas 1877 records Nautilus as cast ashore at Coff's Harbour, north of the Bellinger River in New South Wales. Dr. Curt Teichert from his own observations reports shells of Nautilus repertus Iredale are not uncommon along the shores of Western Australia north of Geraldton; he also states that shells of Nautilus alumnus Iredale are found along the coast of tropical Queensland (letter of September 15, 1948). Nautilus alumnus Iredale has its breeding grounds near the Queensland coast and N. repertus Iredale allegedly lives off the Western Australian coast (Iredale 1944).

Living Nautilus is a relic faunal element because its present range is only a small part of the geographic range of late Tertiary nautiloids. Nevertheless, its range is very large enclosing as it does 60 degrees of longitude and more than 30 degrees of latitude. It is a warm-water, even tropical, form with the center of its distribution between 10° north and 20° south of the equator. However, the one record from South Australia is definitely outside of tropical seas and can hardly be explained by chance distribution through surface ocean currents. More exact data as to temperatures though highly desirable are not available.

Depth

Nautilus is a deep-water form. It is recorded from 385 to 265 fathoms (Dean 1901), 300 fathoms (Griffin 1900), and 315 fathoms (Hoyle 1886). Best catches are made at these depths by native fishermen. It is taken in water of 55 fathoms, although in smaller numbers. At night it migrates in shoals to water as shallow as 3 fathoms and comes quite close to shore (Willey 1899). One specimen was taken by pearl divers in less than 2 fathoms (Dean 1901). Nautilus does not normally come to the surface, and all specimens taken at the surface are probably moribund (Willey 1899). Occasionally live specimens are cast ashore during a heavy gale (Bennett 1859). A list of depth records follows:

(1) Cast ashore during heavy gale. Sometimes taken in fish traps in 3 to 5 fathoms. (Bennett 1859)

(2) Nautilus does not normally come to surface, and all specimens taken from surface are probably moribund. Nautilus migrates in shoals nocturnally from deeper (50-70 fathoms) into shallower water. N. macromphalus ascends at night to as little as 3 fathoms and comes quite close to shore. (Willey 1899)

(3) 66 specimens taken from 1,800 feet deep, others trapped in 6 or 800 feet of water. (Griffin 1900)

(4) Best catches are made in deep water, at a depth from 250 to 400 bracas (= about 450 to 700 meters). It is still taken in water of 100 meters, although in small numbers. A single specimen was taken by pearl divers in less than 4 meters. (Dean 1901)

(5) Off Matuku, Fiji Islands, 315 fathoms, coral mud, living N. pompilius. (Hoyle 1886)

Food

Nautilus has strong jaws and a rasping tongue which are evidently adaptations to food with a hard or leathery skin. It is a carnivore and a scavenger. Its chief foods are small decapod crustaceans, crabs. Bait used by native fishermen in their fish traps, into which Nautilus also goes, varies from a fowl to a sea urchin, from langouste to shrimp, viscera or joints of kid, remains of dogs or cats. Freshness of the bait is not regarded as necessary, as it is said to be fond of decomposing food. The Nautilus caught by natives usually contains crustacean fragments (Bennett 1859; Willey 1899; Dean 1901).

Protective coloration

Shell and soft part have protective coloration. This is well discussed by A. K. Miller.

Sexual dimorphism

Sexes are separate in the Nautilus. Detailed anatomical data are given in many publications, the most comprehensive of which is the monograph by

Griffin. Of immediate interest is the sexual dimorphism of the shell. Dean (1901) noticed that there appeared to be sexual differences, the shell of the female being wider at the sides of the oval aperture and of more angular contour at the umbilical depression. These differences were clear in 6 shells examined, but later Dean found that there must be considerable variation for at another locality he was unable to distinguish male from female shells in as many cases as 3 out of 10. This distinction is, at any rate, impossible in young shells.

Propagation

Eggs are fixed firmly to a suitable surface. One case is reported of the eggs being entangled in sacking fibers after the milk-white capsules had hardened (Willey 1899).

Locomotion

Ever since 1705 when Rumphius published his Amboinsche Rariteitkamer with a figure of a live Nautilus crawling with his tentacles, this idea of the locomotion has continued to crop up in the literature on nautiloids and ammonoids. Even today some modern reconstructions of ammonoids show this mode of locomotion. The observations by Willey and Dean do not support this idea.

The air chambers of the shell of Nautilus serve to buoy the animal so that the only possible position is with the air chambers above the lining chamber. The whole animal is so well balanced that dead animals cannot readily be distinguished from those merely at rest (Dean 1901).

The animal moves by jet propulsion. Water is ejected forcibly through the funnel. Nautilus is a rapid swimmer. In this connection it is worth noting that the animal, shell and all, is excellently streamlined. For descriptions of locomotion, see Willey, Dean, and Tizard.

Parasites

Numerous Copepods are parasitic in the mantle chamber of Nautilus (Willey 1897).

Geographic subspecies

Several "varieties" of Nautilus pompilius Linné were described by the older authors. Even such recent authors as A. K. Miller use "varieties", whatever that term may signify. It seems likely that some "varieties" are local, geographically restricted subspecies. It is also clear that there are sympatric species of Nautilus that do not interbreed. The two new species of living Nautilus described by Iredale in 1944 are the latest descriptions of supposedly new living species. The entire question of geographic subspecies, local variation, and sexual dimorphism of the shell is in great need of statistical investigation and should be a fruitful field of study.

An annotated bibliography follows:

Anderson, C.
The pearly Nautilus--a living fossil: Australian Mus. Mag., vol. 7, pt. 4, pp. 112-115, 1940. [Sydney]

Angas, G. F.
A further list of additional species of marine mollusca to be included in the fauna of Port Jackson and the adjacent coasts of New South Wales: Zool. Soc. London Proc., for 1877, p. 178.

Records Nautilus pompilius and N. macromphalus as "cast ashore at Coff's Harbour, north of the Bellinger River."

Bennett, George
Notes on the range of some species of Nautilus, on the mode of capture, and on the use made of them as an article of food: Zool. Soc. London Proc., pt. 27, pp. 226-229, 1859.

Observations made in the South Seas and collection of second-hand reports. Data on geographic distribution of various species.

Cotton, B. C., and Godfrey, F. L.
A systematic list of the Pelecypoda, Scaphopoda, Cephalopoda and Crepipoda, etc. of South Australia: Malacol. Soc. South Australia, pub. 2, p. 19, Dec. 31, 1940.

Records for Nautilus pompilius Linné: "One record only for South Australia, Foul Bay, Southern Yorke Peninsula, alive, Riddle 1920."

Dean, Bashford
Notes on Living Nautilus: The American Naturalist, vol. 35, pp. 819-837 and p. 1029, 1901.

Observations made in the southern Philippines covering distribution, trapping, shell, general appearance, tentacular movements, and locomotion. An important contribution based on original field observations.

Edwards, F. E.
A monograph of the Eocene Mollusca, etc., pt. 1, Cephalopoda: Palaeontograph. Soc. pp. 1-20, 1849.

Discusses anatomy and ecology from previously published data, largely antiquated.

Griffin, L. E.
The anatomy of Nautilus pompilius: Nat. Acad. Sci. Mem., vol. 8, mem. 5, 197 pp., 17 pls., 1900.

A detailed and excellent anatomical description based on 66 specimens from 1,800 feet deep off southern coast of Negros, Philippine Islands. Chiefly anatomical but contains a few ecological notes at the beginning; bibliography of titles on living Nautilus is excellent.

Hawley, J. R.
The pearly Nautilus: Australian Nat., vol. 10, no. 4, pp. 148, 1938. [Sydney]

Hoyle, W. E.
Report on the Cephalopoda collected by H. M. S. Challenger during the years 1873-76: Report on the Scientific results of the voyage of H. M. S. Challenger, etc., Zoology--vol. 16, pp. 199-221, 1886.

Same as description in Tizard 1885.

Iredale, T.
Australian pearly Nautilus: Australian Zool., Sydney, vol. 10, no. 3, pp. 294-298, 1944.

Describes 2 new living species: N. alumnus Iredale, Queensland and N. S. Wales; N. repertus Iredale, Pelsart Island, Abrolhos W. A. = M. ambiguus Sowerby, no locality.

Kershaw, J. A.
Notes on the Argonauts: Victorian Naturalist, vol. 19, pp. 28-32, 1902.

Lever, R. J. A. W.
Further notes on the fauna of the British Solomon Islands Mollusca: Tropical Agric. Jour., Imp. Coll. Trop. Agric. Trinidad, vol. 20, no. 2, p. 42, 1943.

Miller, A. K.
Tertiary Nautiloids of the Americas: Geol. Soc. America, Mem. 23, pp. 13-20, 1947.

Contains a chapter on living Nautilus based on published data, with an excellent discussion of protective coloration of the shell. Paleontologic-literature index particularly complete.

Mugglin, F.
Beiträge zur Kenntniss der Anatomie von Nautilus macromphalus G. B. Sow (erby): Gesell. Vierteljahrschr. naturforsch. Zürich, vol. 84, nos. 1 & 2, pp. 25-118, 1939.

Powell, A. W. B.
The shellfish of New Zealand, 2nd ed., p. 52, 1946: Whitcombe & Tombs Limited.

Records: "Not infrequently the shells of the tropical chambered Nautilus, both N. pompilius and N. macromphalus, wash ashore on the Ninety-mile Beach, ... the occurrence of these shells on a New Zealand beach is no evidence that the species live here."

Pruvot-Fol, A.
Remarques sur le Nautile: Internat. Cong. Zool., vol. 12, pp. 1652-1663, Lisboa 1937.

Riddle, A. R.
An adventitious occurrence of Nautilus pompilius Linné: Royal Soc. South Australia Trans., vol. 44, pp. 257-262, 1920.

Schenck, H. G.
Cephalopods of the genus Aturia from western North America: California Univ., Dept. Geol. Sci. Bull., vol. 19, no. 19, pp. 435-490, 1931.

Contains a chapter on mode of living.

Tizard, T. H., Moseley, H. N., and others
Narrative of the cruise of H. M. S. Challenger etc.: Report on the scientific results of the voyage of H. M. S. Challenger etc., Narrative--vol. 1, pp. 490-491, 1885. (quoted by Hoyle)

Verco, J. C., and Cotton, B. C.
South Australian Cephalopoda: South Australian Mus. Rec., vol. 4, pp. 125-133, 1928.

Willey, Arthur
Letters from New Guinea on Nautilus etc.: Quart. Jour. Micr. Sci., n. s., vol. 39, pp. 145-180, 1897.

Important and based on original observations.

Willey, Arthur
Zoological observations in the South Pacific: ibidem, n.s., vol. 39, pp. 219-231, pl. 13, 1897.

Important original observations.

Willey, Arthur
The adhesive tentacles of Nautilus, etc.: ibidem, n.s., vol. 40, pp. 207-209, 1898.

Anatomical.

Willey, Arthur
The pre-ocular and post-ocular tentacles and osphradia of Nautilus: ibidem, n.s., vol. 40, pp. 197-202, 1898.

Anatomical.

Willey, Arthur
General account of zoological expedition to the South Seas during the years 1894-1897: Zool. Soc. London Proc. for 1899, pp. 7-9, 1899.

Observations made in New Britain. Data on food, depth distribution, locomotion, geographic distribution of species.

Willey, Arthur
Contribution to the natural history of the Pearly Nautilus: Zoological results based on material from New Britain, New Guinea, Loyalty Islands, and elsewhere, etc., pt. 6: Cambridge Univ. Press, 1902.

ECOLOGY OF MARINE BIRDS

by

Herbert Friedmann
U. S. National Museum

The references listed below contain a large amount of information concerning geographical distribution, life histories, and physical adaptation of Recent birds, all of which are necessary to the student who wishes to reach an understanding of the environment of extinct birds. The annotated ecologic references are as follows:

Alexander, W. B.
Birds of the Ocean: 428 pages, 1928.

Although primarily a manual for the identification of birds seen at sea, this book contains discursive data on ecological distribution of marine birds. It is world-wide in scope.

Andersson, K. A.
Das höhere Tierleben im antarktischen Gebiete: Wissenschaftl. Ergebnisse der Schwedischen Südpolar-Exped., 1901-1903, vol. 5, Zool., i, Vögel, 19-58, pls. 1-10, 1908.

Bannerman, David A.
The distribution and nidification of the Tubinares in the North Atlantic Islands: Ibis (10), vol. 2, pp. 438-494, 1914.

A detailed study of the distribution of petrels and shearwaters.

Beddard, F. E.
Notes on the visceral anatomy of birds. No. 2. On the respiratory organs in certain diving birds: Proc. Zool. Soc. London, pp. 252-258, 1888.

Bennett, A. G.
The adaptability of subantarctic and antarctic birds to local conditions: Emu, vol. 26, pp. 259-263, 1927.

Bent, A. C.
1. Life Histories of North American Diving Birds: U. S. Nat. Mus. Bull. 107, 245 pp., 95 pls., 1919.

Complete accounts of the habits of the Alcidae, Colymbidae, and Gaviidae of North America. The members of the first family are all marine.

2. Life Histories of North American petrels and pelicans and their allies: U. S. Nat. Mus. Bull. 121, p. 343, 69 pls., 1922.

The species of albatrosses, shearwaters, and petrels (all marine) occurring in North America are here treated in detail.

Bergmann, A.
Ueber die Verhältnisse der Wärmeökonomie der Thiere zu ihrer Grösse: Göttinger Studien, pt. 1, pp. 595-708, 1847.

A useful study of body size and temperature regulation, with many data from marine birds.

Boubier, Maurice
La distribution geographique des Manchots (Spheniscides) et son interpretation geophysique: Rev. Franc. d'Ornith., vi, pp. 131-136, 1919.

Distribution of penguins as related to geophysical factors.

Brooks, S. C.
Oceanic Currents and the Migration of Pelagic Birds: Condor, xxxvi, pp. 185-190, 1934.

Clarke, W. E.
1. Ornithology of the Scottish National Antarctic Expedition. Sect. 5 - On the Birds of the South Orkney Islands: Sci. Res. Scot. Nat. Antarct. Exp., vol. 4, pp. 219-247, 1913.

2. On the birds of the Weddell and adjacent seas: ibid., vol. 4, pp. 255-270, 1913.

3. On the birds of Gough Island, South Atlantic Ocean: ibid., vol. 4, pp. 277-289, 1913.

These three papers all on habits of birds.

Coker, R. E.
Habits and economic relations of the guano birds of Peru: Proc. U. S. Nat. Mus., vol. 56, pp. 449-511, 1919.

An extensive account of the cormorants, pelicans, and boobies of the Peruvian coast, and their food supply as influenced by the Humboldt Current.

Dabelow, A.
Die Schwimmanpassungen der Vögel. Ein Beitrag zur biologischen Anatomie der Fortbewegung: Morph. Jahrb., vol. 54, pp. 288-321, 1925.

Adaptation of birds to swimming.

Falla, R. A.
The Distribution and Breeding Habits of Petrels in Northern New Zealand: Rec. Auk. Inst. Mus., i, no. 5, pp. 245-260, 1934.

Fisher, W. K.
Birds of Laysan and the Leeward Islands, Hawaiian Group: Bull. U. S. Fish Commission, xxiii, pp. 769-807, 1906.

Life histories of marine birds, especially albatrosses and shearwaters.

Gillespie, T. H.
A Book of King Penguins: 1932.

Life history data, considerably padded by literary and sentimental verbiage.

Groebbels, Franz
Der Vogel
1. Band: Atmungswelt und Nahrungsvelt, 918 pages, 1932.
Der Vogel
11. Band: Geschlecht und Fortpflanzung, 547 pages, 1932.

These volumes summarize a vast amount of data on respiration, nutrition, and reproduction in birds. The data pertaining to oceanic species are readily found from the systematic indices.

Gross, A. O.
The life history cycle of Leach's Petrel (Oceanodroma leucorhoa leucorhoa) on the outer sea islands of the Bay of Fundy: Auk, lii, pp. 382-399, 1935.

Hagerup, O.
Communities of birds of the northern Atlantic Ocean: Videns. Medd. Dansk. Naturhist. Forening: Kobenhavn, lxxxii, pp. 127-151, 1926.

Jacobi, A.
Über Stammesgischichte and systematische Stellung der Impennes: Ber. 5. Internat. Ornith. Kongr., Berlin, 1910, pp. 216-220, 1911.

Evolution and taxonomy of penguins.

Jespersen, Paul
Fuglemaengden paa det nordlige Atlanterhav og dens Afhaengighed af Planktonmaengden. The Frequency of Birds over the High Atlantic Ocean and Its Relation to the Quantity of Macroplankton: Nat. Verd. Kobenhavn, ix, pp. 337-350, 1925.

Lavalle y Garcia, J. A. de
1. Informe preliminar sobre la causa de la mortalidad anormal de las aves ocurida en el mes de marzo de presente ano: Memoria de la Compañia Administradora del Guano, viii, pp. 61-88, 1917.

Mortality studies of cormorants, boobies, and pelicans on the Peruvian coast.

2. Datos para el estudio de la relacion entre las epocas de realizacion de las principales faces de la vida de las aves y las condiciones climatericas: Memoria de la Compañia Administradora del Guano, ii, pp. 77-168, 1920.

Peruvian cormorants, boobies, and pelicans.

Levick, G. M.
Antarctic Penguins. 1914.

Good accounts of habits of several species, in particular the Adelie Penguin, Pygoscelis adeliae.

Lewis, H. F.
The Natural History of the Double-Crested Cormorant. Ottawa. 99 pages, 1929.

Lockley, R. M.
Shearwaters. 238 pages, 1942.

Good life-history material of oceanic birds, chiefly of one species, the Manx Shearwater.

Lowe, P. R.
On the classification of the Tubinares or petrels: Proc. Zool. Soc. London, pt. 4, pp. 1433-1443, 1926.

Murphy, Robert Cushman
1. Oceanic Birds of South America: 2 vols., 1936.

The first volume contains the most extensive discussion of marine ecology as related to birds available and a digest of most of the earlier literature. Both volumes give detailed life histories of all the included species of birds.

2. The Littoral of Pacific Colombia and Ecuador and Racial Succession in the Colombian Choco: Geogr. Rev., xxix, pp. 1-33; 461-471, 1939.

Ecology of marine birds.

Neu, W.
Die Schwimmanpassunger der Tauchvögel (Blässhuhn und Pinguine). Zeitschr. vergl. Physiol: Abt. C., Zeitschr. wiss. Biol. xiv, pp. 682-708, 1931.

Adaptation to swimming of penguins, etc.

Paessler, R.
Beiträge zur Verbreitung der Seevogel: Journ. f. Ornith., lxi, pp. 41-51, 1931.

Distribution of marine birds.

Richdale, L. E.
1. Supplementary Notes on the Royal Albatross: Emu, xli, pp. 169-184; 253-264, 1942.

2. The Kuaka or Diving Petrel, Pelecanoides urinatrix (Gmelin): Emu, xliii, pp. 24-107, 1943.

3. The White-faced Storm Petrel: Trans. Roy. Soc. New Zealand, lxxiii, pt. 2, pp. 97-115; 217-232; 335-350, 1943-4.

4. The Parara or Broad-billed Prion, Pachyptila vittata (Gmelin): Emu, xliii, pp. 191-217, 1944.

5. The Titi Wainui or Fairy Prion, Pachyptila turtur (Kuhl): Trans. Roy. Soc. N. Zealand, lxxiv, pp. 32-48; 165-181.

All of Richdale's papers are detailed studies of habits.

Rosenberg, F. T.
Beitrag zur Entwicklungsgeschichte und Biologie der Colymbidae: Zeitsch. wiss. Zool. 97, p. 199-217, 1911.

Development and habits of grebes.

Shufeldt, R. W.
Contributions to the comparative osteology of arctic and subarctic water birds: Journ. Anat. Phys. London, xxiii, pp. 1-39, 165-186, 400-427; xxiv, pp. 89-116, 169-187, 543-566; xxv, pp. 60-77, 1888-89.

Vogt, Wm.
1. Aves guaneras: Bol. de la Compañia Administradora de Guano, xviii, no. 3, pp. 3-132, 1942.

Detailed report on the cormorants, boobies, and pelicans of the Peruvian coast.

2. An ecological depression on the Peruvian coast: Proc. 8th Am. Sci. Congr., vol. 3, pp. 507-527, 1942.

Population studies of cormorants, boobies, and pelicans of Peru.

Wynne-Edwards, V. C.
On the habits and distribution of birds on the North Atlantic: Proc. Boston Soc. Nat. Hist., xl, pp. 233-346, 1935.

PALEOECOLOGY OF TERTIARY NAUTILOIDS

by

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Those who have collected and described Tertiary nautiloids have generally refrained from discussing the ecology of these fossil cephalopods and there are many good reasons for such omission. One of the reasons is the comparative paucity of material. At Tertiary localities, where countless other marine mollusks can be collected, usually only a very few nautiloids can be found. If one estimates the relative abundance of individuals belonging to the various classes of the Mollusca in an average Tertiary deposit one finds that there are in excess of 1,000 other mollusk specimens to 1 nautiloid shell. The proportion may even surpass 10,000 to 1. Such scarce material does not invite ecologic interpretation.

In the past those who have collected Tertiary nautiloids in the field have been preoccupied with other problems connected with them. The chief of these problems was, and it is not yet fully solved, the stratigraphic range and succession of the several Tertiary genera. For instance, until 1935 practically nothing was known about the stratigraphic range of the comparatively common genus Aturia in the Gulf Coastal Plain. Significant extensions of the range of this genus in that area were discovered by Barry and LeBlanc (1942) and Stenzel (1940). The establishing of stratigraphic ranges of nautiloids in the Gulf Coastal Plain can be rated as one of recent accomplishments in that area.

Another reason for the lack of discussion of ecology in connection with Tertiary nautiloids is the obvious fact that there are much better study materials available; namely, the living species of Nautilus. Tertiary species, no matter to which genus they belong, are so closely related to Nautilus that whatever observations can be made on living Nautilus should be immediately applicable to fossil forms.

Strictly ecological data on Tertiary nautiloids based on Tertiary materials have not been published. The articles listed below are based on living nautiloids insofar as they discuss ecology. The reader is referred to the "Annotated bibliography of living Nautiloids" in this volume.

Barry, J. O'K., and LeBlanc, R. J.
Lower Eocene faunal units of Louisiana: Louisiana Geol. Survey, Geol. Bull. 23, pp. 76-77, 1942.

Davies, A. M.
Tertiary Faunas, vol. 2, The sequence of Tertiary faunas, pp. 63, 69, 71, 81, 85, 86, 104, 112, 121, 140, 214, Thomas Murby & Co., 1934.

Paleoclimatological distribution and evaluation of Nautilus.

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Diener, C.
Grundzüge der Biostratigraphie, p. 76, 1925.

Edwards, F. E.
A monograph of the Eocene Mollusca, etc., pt. 1, Cephalopoda: Palaeontograph. Soc. pp. 1-20, 1849.

Discusses anatomy and ecology from previously published data, largely antiquated.

Lang, W. D.
Ammonites: Dorset Nat. Hist. Field Club Proc., vol. 61, pp. 98-116, 1940.

Miller, A. K.
Tertiary Nautiloids of the Americas: Geol. Soc. America, Mem. 23, pp. 13-20, 1947.

Contains a chapter on living Nautilus based on published data, with an excellent discussion of protective coloration of the shell. Paleontologic literature index particularly complete.

Schenck, H. G.
Cephalopods of the genus Aturia from western North America: California Univ., Dept. Geol. Sci. Bull., vol. 19, no. 19, pp. 435-490, 1931.

Contains a chapter on mode of living.

Spath, L. F.
On the classification of the Tertiary Nautili: Annals and Mag. Nat. History, ser. 9, vol. 20, p. 424, 1927.

Discusses classification, stratigraphic ranges, and evolution and the nautiloid species of the London clay.

Stenzel, H. B.
Tertiary nautiloids from the Gulf Coastal Plain: Texas Univ. Pub. 3945, pp. 717-794, pls. 34-42, 1940.

Stratigraphic ranges of Tertiary Nautiloids in the Gulf Coastal Plain of North America.

PALEOECOLOGY OF BIRDS

by

Herbert Friedmann
U. S. National Museum

Despite the scarcity of fossil bird remains it is possible to reach reasonably valid conclusions on the paleoecology of some marine bird types because some of the oldest known birds (Ichthyornis and Hesperornis of the Cretaceous, and the Eocene penguins) represent a marine environment. Because of the delicacy of bones of those which retained the power of flight, investigations of their paleoecology are to a great degree limited to speculations based on analogy with modern conditions and faunas. For this reason several papers dealing primarily with recent ecology are included in this bibliography.

Abel, O.

1. Grundzüge der Paleobiologie der Wirbeltiere: 284 pages, 1912.

   Of general interest, with many suggestive hints regarding fossil birds.

2. Eroberungszüge der Wirbeltiere in die Meere der Vorzeit: 1924.

   Suggestive data on adaptability of vertebrates, including birds, to marine conditions in ancient times.

3. Lebensbilder aus der Tierwelt der Vorzeit: 411 pages, 1927.

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ENVIRONMENTAL CONDITIONS OF DEPOSITION IN THE GULF OF MEXICO

by

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The environmental conditions of deposition in the Gulf of Mexico are of two distinct types: (1) the present warm-water environment, and (2) the cold-water environment of the waning stages of the Ice Age. This latter environment is found within 2 to 10 feet of the surface of the present deposits throughout the deep-water areas of the Gulf of Mexico.

Sediments representing these two environmental types were collected during the winter and spring of 1947 in the course of a joint investigation by Woods Hole Oceanographic Institution and the Geological Society of America. Henry C. Stetson, Fred B. Phleger, Jr., and myself participated in this work. Twelve traverses were run across the continental shelf of the Gulf of Mexico between the Mississippi River and the Rio Grande, and seven traverses down the continental slope and out into the abyssal deep. In all, 550 short cores one to two feet in length; and 100 long cores, 3 to 11 feet in length were collected. In addition about 100 stations were occupied for plankton tows, serial temperature, and samples of water. Several hundred temperature-depth records were made with a bathythermograph along the lines of traverse, and continuous depth records were made with a recording fathometer. The material collected is being studied under the auspices of Woods Hole Oceanographic Institution. The U. S. Bureau of Mines Central Experiment Station at Pittsburgh, Pa., through the courtesy of H. M. Cooper, Supervising Chemist of the Coal Analysis Section, is cooperating with the project by making analyses of the organic content of the sediments.

The working up of the results of the expedition is incomplete. Three short reports summarizing the results obtained thus far have been prepared:
(1) "Recent changes in sedimentation in the Gulf of Mexico" by Parker D. Trask, Fred B. Phleger, Jr., and Henry C. Stetson: Science, vol. 106, pp. 460, 461, 1947.
(2) "Subarctic sediments in the Gulf of Mexico," by Parker D. Trask, Henry C. Stetson, and Fred B. Phleger, Jr. (Abstract): Geol. Soc. America Bull., vol. 58, p. 1233, 1947.
(3) "Origin and rate of deposition of deep sea sediments," by Fred B. Phleger, Jr. To be published in the Trans. Amer. Geophys. Union, vol. 29, 1948.

The sediments now being deposited in the Gulf of Mexico consist of coarse silt on the continental shelf, fine clay on the continental slope, and foraminiferal ooze in the abyssal deeps. On the continental shelf, especially off the coast of Texas near Galveston, zones of sand are found about midway across the shelf. These sand zones may constitute former beaches formed when the level of the Gulf was lower, they may represent submerged bars or water dunes now in the process of formation, or they may be due to some other cause. At any rate, zones of sand much coarser than the adjoining silt are found in at least two places across the shelf.

The calcium carbonate content of the sediment increases more or less progressively seaward, being about 5 percent in shallow water and more than 30 percent in the center of the Gulf. The maximum observed is about 40 percent. In the deeper parts of the Gulf a large part of the calcium carbonate content is due to Foraminifera. The distribution of calcium carbonate in the Gulf thus is similar to that in the ancient Upper Cretaceous geosyncline in Wyoming where the calcium carbonate content increases from less than 10 percent in western Wyoming to slightly more than 30 percent in southeastern Wyoming. Both in the Gulf and in the Upper Cretaceous geosyncline of Wyoming the rate of increase per mile is of the same order of magnitude.

The organic content of sediments in the Gulf likewise increases seaward in much the same way as it does in the Upper Cretaceous geosyncline, though the quantity of carbon compounds preserved in the sediments of the Gulf is much less than in the Upper Cretaceous geosyncline, presumably due to lower productivity of organisms in the overlying water. The sediments on the continental shelf contain less than one percent organic matter, on the continental slope 1.0 to 2.0 percent, and in the abyssal deeps about 1.0 percent. The organic content is greatest on the continental slope. Two factors could contribute to this greater organic matter content on the continental slope: (1) organic matter might be washed from the adjoining continental shelf by the winnowing action of the water, and (2) the productivity of organic matter in the sea may be greater over the continental slope where perhaps there is more turbulence in the water, thus providing more nutrients for the plankton. The increased organic content on the continental slope, where initial dips are likely to be greater than on the adjoining continental platform or in the deeps, suggests that oil geologists might look for increased initial dip in their search for oil, because such increased concentrations of organic matter adjacent to the coarser sediments found on the continental shelf might point to localities favorable for accumulation of oil.

Submarine ridges or humps rise 300 to 400 feet above the continental platform in some places off the west coast of Louisiana. These seamounts have been thought to represent salt domes, but the sediments now lying on them are very similar to ancient bioherms or reefs. On the adjoining continental platform the sediments are silt of clastic origin, on the slopes on the side of the seamount they are marl, and on top they consist of lithothamnium balls and corals with very little sand or silt. As some of these seamounts rise to within 10 fathoms of the surface, their crests must be subject to considerable winnowing action when tropical hurricanes pass over them, thus accounting for the lack of fine sediment.

No material changes in sedimentation are noted in relation to depth of burial on the continental platform or on the continental slope, but in the abyssal deeps the marl and foraminiferal ooze give way at depth of 2 to 10 feet to alternating sand, silt, and clay containing a subarctic foraminiferal fauna. The present deposits in the upper layers contain a subtropical fauna dominated by Globigerinoides rubra, Globorotalia menardii, G. tumida, G. truncatulinoides, and Pulleniatina obliquilata. The clay beneath contains Globigerina bulloides, G. Pachyderma, and small specimens of Globigerina rubra.

The transition between the cold and warm fauna in most places is abrupt, but in three places a zone of red mud, 6 inches thick, with an intermediate

fauna and intermediate calcium carbonate content, is found between the warm and cold zones. If such a zone were found in the deep sea it would be called red clay, but as it contains considerable terrigenous material it is called red mud. The mode of origin of the red color and of the intermediate calcium carbonate content very likely is similar to the mode of origin of the red color in typical deep-sea red clay.

The zone of sediments containing the cold water fauna is found at progressively shallower depths beneath the sediments seaward in the Gulf, thus indicating a more rapid rate of sedimentation near shore.

The most amazing aspect of the cold water sediments is the presence of numerous well-sorted silt zones, 0.2 mm. to 50 millimeters in thickness. Most of these silt zones are extremely well sorted, and the median diameter of silt grains is between 10 and 20 microns. The origin of such well-sorted silts having such small diameters is an enigma. The sorting is too good to suggest normal winnowing caused by simple settling through the water. A current action seems more probable.

A few of the coarse zones consist of sand. Two of these sand zones exhibit cross bedding, though, because of the small diameter - two inches - of the cores, the cross bedding might be due to ripple marks rather than to typical cross bedding. Whether due to ripple marks or to cross bedding, the angle of inclination of the bedding, deviating up to 15° from the horizontal, suggests current action.

This cross bedding is found at depths of several thousand feet, and the cross-bedded zones are overlain by several feet of sediments. If just these two instances of cross bedding were all the seemingly anomalous sediments found, not much concern would be displayed; but in two other places, in more than 11,000 feet of water and at least three feet beneath the surface of the sea bottom, zones of well-sorted medium-grained sand are present. One of these zones is about 12 inches thick and the other is three feet thick. The explanation of such thick masses of sand in water so deep is a real challenge to the scientist.

Normally, cross bedding and well-sorted sands are taken as indications of shallow water origin. If that is true, then either the level of the water in the Gulf of Mexico was ten or eleven thousand feet lower during the Ice Age, or the sea floor has been lowered a like amount since the end of the Ice Age 25,000 to 100,000 years ago. Either idea seems unorthodox. If one refuses to consider the possibility of shallow water origin, then he must assume that such cross-bedded and well-sorted sediments accumulate in deep water, perhaps because of some yet unexplained currents; but if he makes that assumption, what becomes of the time-honored concept of shallow water origin of geosynclines? Perhaps geologists had better not place too much confidence in cross bedding and well-sorted sands as evidence of shallow water in geosynclines. Maybe geosynclines are in part basins in which rate of sedimentation was not always equal to rate of settling. Perhaps some of them were deep troughs that finally were filled with sediment.

RECENT SHALLOW WATER FORAMINIFERAL ASSEMBLAGES FROM NIIGATA PREFECTURE, JAPAN [12]

by

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and
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ABSTRACT

The shallow water foraminiferal assemblage of the Japan Sea off the coast of Niigata Prefecture, Japan, is essentially a miliolid-Rotalia - Elphidium faunule with subordinate Buliminidae and Discorbis and rarer arenaceous and polymorphinid elements. The foraminiferal faunule of the Pliocene Haizume formation of Niigata Prefecture is regarded as having been developed in somewhat deeper-water and cooler conditions than the environment of the Recent assemblages described herein.

INTRODUCTION

As a basis for paleo-ecologic study of the late Tertiary and Quaternary foraminiferal faunules in the Tertiary embayment of Niigata, littoral and sublittoral bottom samples were collected from the Japan Sea off the coast of Niigata Prefecture near Kashiwazaki, Kujiranami, and Ishiji during August 1947.

Six bottom samples were taken by snapper dredge from locations indicated in table 1. Samples OM-498 and OM-584 were taken from areas between reefs of mudstone belonging to the Shiiya formation.

TABLE 1 - LIST OF SAMPLES

Sample No.	Location	Depth in meters	Character of bottom	Weight of sample (gm)
OM-498	Ishiji	1.5	Silty sand	70
OM-584	Ishiji	5	Silty sand	120
O-2006	Kashiwazaki	8	Silty sand	50
O-2007	Kashiwazaki	9	Silty sand	50
O-2009	Kujiranami	16	Silty sand	150
O-2008	Kashiwazaki	39	Silty sand	90

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[12] Published by permission of the Chief, Natural Resources Section, General Headquarters, Supreme Commander for the Allied Powers. This paper forms part of a research project initiated by Natural Resources Section for the purpose of assembling paleontologic data applicable to petroleum exploration in Japan.

Measured quantities of the samples were sieved through a set of three screens of 45, 60, and 120-mesh. Foraminifera were hand-picked from residues held on the 45-mesh screen, but were separated by carbon tetrachloride flotation from the residues held by the finer screens. Qualitative and quantitative analyses of the foraminiferal assemblages of each sample were made by actual count.

The samples were collected by T. Oinomikado, paleontologist and S. Omachi, geologist, of Imperial Oil Co. Determination of the assemblages was carried out by T. Oinomikado and the analysis of the relations between assemblages and environment was made by L. W. Stach.

ENVIRONMENTAL FACTORS INFLUENCING THE ASSEMBLAGES

In the Japan Sea, between Sado Island and the coast of Niigata Prefecture, a warm current flows near the surface, and a cool current flows at 200 meters or more in depth. All samples collected were taken from depths within the influence of the warm surface current of which the seasonal temperature range is from 9°C to 25.5°C. The graph (figure 1) shows the mean monthly temperature at the surface, at 25 meters, and at 50 meters depth over the period 1917-1931 at a station five miles off Teradomari on the Niigata coast along a line to Akadomari on Sado Island; this station was selected from a series of five stations along this line, but there is no significant difference in recorded temperatures at different depths from each of these stations.

The graph (figure 1) also shows that the minimum temperature at all three depth stations is the same and that there is no significant difference between the maximum temperature reached by the surface water and that of the water at 25 meters; maximum temperature at 50 meters depth is not more than 5°C lower than at the shallower depths. It may therefore be concluded that temperature could have no effect on quantitative or qualitative characteristics of the assemblages in the samples studied, with the possible exception of sample 0-2008 which was taken from 39 meters; the assemblages of these samples were developed within a temperature range of 9°C to 25.5°C.

All samples were taken within a narrow depth range at short distances from the shoreline. During the warmer months the Japan Sea is generally calm and subject only to occasional swells, but during the winter months the sea near the Niigata coastline is strongly disturbed and wave action is great over long periods; longshore currents are in evidence throughout the year. Along the exposed Niigata coastline, considerable transportation of foraminiferal tests from their original source could be expected, at least within the limiting depths of wave action. Considering this factor, it is unlikely that all components of the assemblages recorded were actually developed in situ, and it is probable that mingling and selective sorting of components from different types of environment, caused mainly by variations in the substratum, has taken place. The determination of autochthonous elements in such samples would require much more detailed investigation.

All samples, independent of depth, were taken from silty sand bottom. However, considerable variation in the character of the substratum on the sea bottom off the Niigata coast can be inferred, because it is known that rock

reefs are common on the sea bottom along the Niigata coastline. The intersperal of rocky reefs and silty sand bottom provides conditions for the development of different types of algal associations which in turn influence the character of the foraminiferal assemblages developed on these different types of substratum.

The formations which crop out both on the sea bottom and along the shore in this region belong to the Teradomari black shale formation and the Shiiya alternation of sandstones and mudstones; no younger formations other than Quaternary sand dunes are found along this part of the coast. The assemblages of the Miocene formations are characterized by the common occurrence of species of Uvigerina, Listerella, and Cyclammina; of these genera only a few specimens of Uvigerina were found in the Recent deposits, but the mode of preservation is different from that of Uvigerina in the Miocene formations. It can therefore be assumed that no derived tests are present in the bottom samples. The assemblages recorded from these bottom samples are regarded as a group which is, in general, representative of shallow water conditions within a temperature range of 9°C to 25.5°C, under average conditions of salinity, on a substratum of variable character ranging from barren silty sand to algal associations on rocky reefs.

NOTES ON THE ASSEMBLAGES

The assemblages of the samples are shown in table 2. As all samples were taken in a narrow depth range, at short distances from the shore, within the limits of wave action, and under the influence of longshore and bottom currents, it is probable that the assemblages of the individual samples do not represent assemblages in place, and that admixture and selective sorting have probably affected both the qualitative and quantitative characters of the assemblages. It is safer to consider these assemblages as a group representative of the general assemblage type present in this area, rather than to attempt to infer that the differences between individual assemblages are due in this case to variations in environmental conditions; the small number of samples studied is not sufficient to support any such inferences which might be made.

TABLE 2 - SHALLOW WATER FORAMINIFERA, NIIGATA PREFECTURE

List of Foraminifera	Sample No.					
	Om-498	Om-584	0-2006	0-2007	0-2009	0-2008
Astrorhizidae						
Rhabdammina sp.	0	0	0	0	0	1
Reophacidae						
Reophax bilocularis Flint	0	0	0	0	0	1
Reophax sp.	0	0	0	0	0	1
Ammodiscidae						
Glomospira gordialis (Jones and Parker)	0	0	0	0	0	1

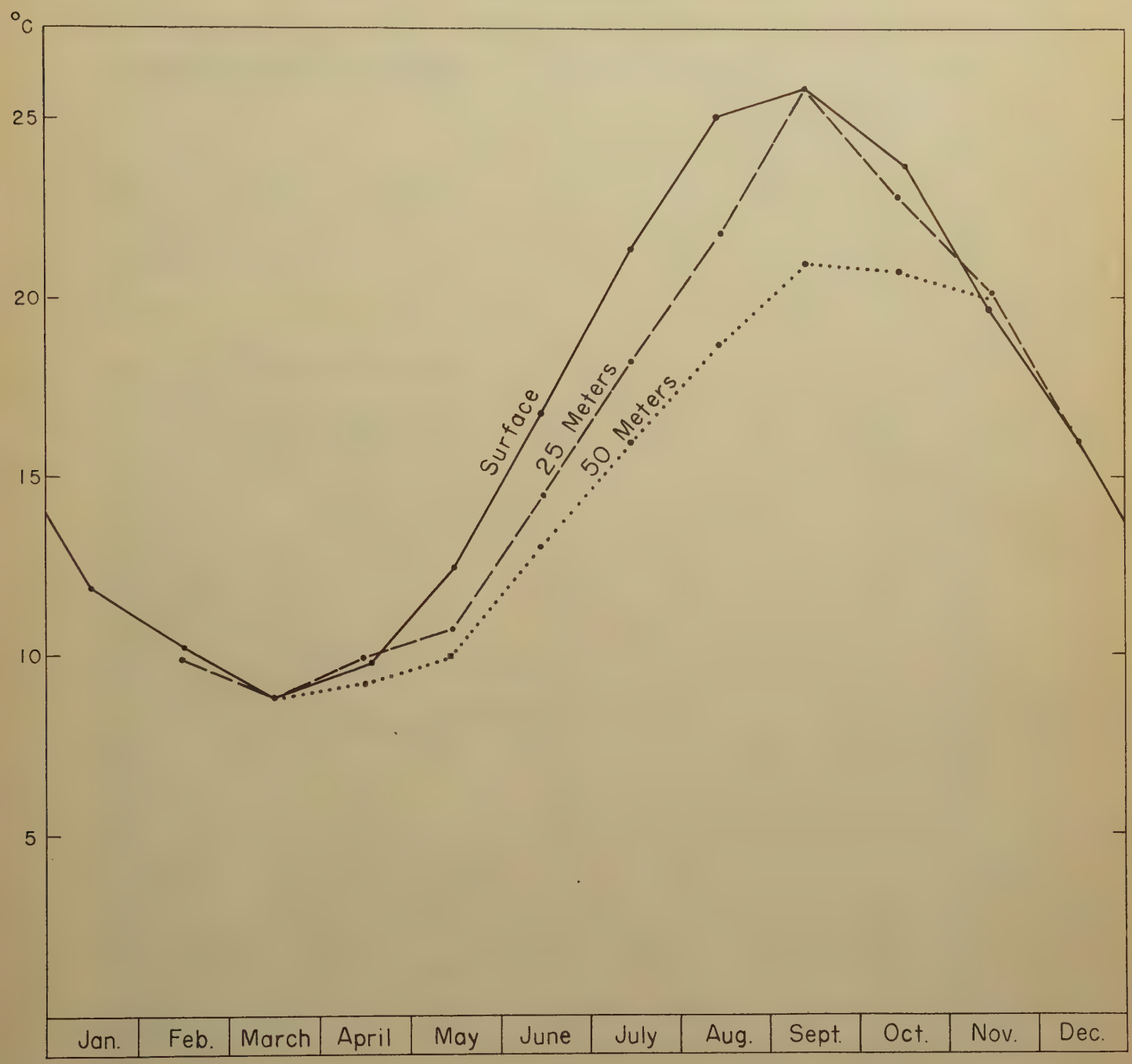

Figure 1 - Average monthy temperatures, 1917 - 1931, at station 5 miles off Teradomari, Niigata Prefecture, Japan.

List of Foraminifera	Sample No.					
	Om-498	Om-584	0-2006	0-2007	0-2009	0-2008
Lituolidae						
Ammomarginulina pseudospirale (Williamson)	0	0	0	0	0	2
Textulariidae						
Textularia gramen d'Orbigny	0	0	0	0	2	0
Textularia parvula Cushman	0	0	0	0	46	5
Textularia sp. (A)	0	0	6	11	574	0
Textularia sp. (B)	0	0	0	0	59	0
Miliolidae						
Quinqueloculina lamarckiana d'Orbigny	0	0	1	0	0	1
Quinqueloculina parkeri (Brady)	0	9	0	0	0	0
Quinqueloculina pygmaea Reuss	0	0	1	0	0	0
Quinqueloculina rugosa d'Orbigny	0	10	0	0	1	0
Quinqueloculina seminula (Linné)	0	6	4	2	77	52
Quinqueloculina vulgaris d'Orbigny	8	7	0	0	8	2
Quinqueloculina yabei Asano	1	251	0	0	0	0
Quinqueloculina sp. (T 7)*	1	23	15	0	15	0
Quinqueloculina sp. (T 9)*	0	2	0	0	0	0
Quinqueloculina sp. (T 10)*	0	0	1	0	0	0
Massilina inaequalis Cushman	0	113	0	0	11	0
Massilina cf. M.secans (d'Orbigny)	0	85	6	39	61	6
Massilina sp.	0	0	0	0	41	0
Spiroloculina antillarum d'Orbigny	2	33	0	0	0	0
Spiroloculina hadai Thalmann	0	0	0	0	1	0
Spiroloculina sp.	0	0	0	0	0	1
Articulina sp.	0	0	0	0	0	1
Hauerina bradyi Cushman	1	79	0	0	0	0
Triloculina oblonga (Montagu)	2	5	0	0	2	0
Triloculina terquemiana (Brady)	0	31	0	0	0	0
Triloculina tricarinata d'Orbigny	0	5	0	0	1	1
Triloculina trigonula (Lamarck)	9	28	0	0	17	3
Miliolinella circularis (Bornemann)	0	168	1	0	2	0
Miliolinella circularis lineata (Brady)	9	30	0	0	0	0
Flintia sp.	0	0	0	0	1	0
Pyrgo yabei Asano	0	15	0	0	1	0
Pyrgo sp.	0	67	0	0	0	0
Ophthalmidiidae						
Nodobacullariella insignis (Brady)	0	1	0	0	0	0
Vertebralina striata d'Orbigny	5	67	0	0	1	0
Parrina bradyi (Millett)	0	21	0	0	0	0

List of Foraminifera	Sample No.					
	Om-498	Om-584	0-2006	0-2007	0-2009	0-2008
Trochamminidae						
Trochammina globigeriniformis (Parker and Jones)	3	39	0	0	60	4
Trochammina inflata (Montagu)	0	8	0	0	3	54
Trochammina squamata Jones and Parker	0	2	0	0	1	0
Lagenidae						
Lagena squamosa (Montagu)	0	2	0	0	0	0
Lagena striata strumosa Reuss	0	0	0	0	0	1
Polymorphinidae						
Glandulina laevigata d'Orbigny	0	1	0	0	0	0
Glandulina rotundata (Reuss)	0	0	0	0	0	1
Pseudopolymorphina ishikawaensis Cushman and Ozawa	0	0	0	0	1	1
Pseudopolymorphina okuwaensis Cushman and Ozawa	0	0	0	0	1	8
Pseudopolymorphina cf. P.suboblonga jugosa Cushman and Ozawa	0	0	0	0	0	2
Sigmoidella kagaensis Cushman and Ozawa	0	0	0	0	0	2
Nonionidae						
Nonion manpukuziensis Otsuka	0	0	0	0	0	4
Nonion turgida (Williamson)	0	0	1	0	0	13
Nonionella sp.	0	0	0	0	5	0
Pseudononion japonicum Asano	9	24	7	1	7	0
Elphidium advenum (Cushman)	1	63	0	0	0	0
Elphidium craticulatum (Fichtel and Moll)	0	3	0	0	0	3
Elphidium "crispum"(Linné)	13	356	4	0	27	1
Elphidium jenseni (Cushman)	1	36	19	0	6	1
Elphidium cf. E.lessoni (d'Orbigny)	0	0	5	3	0	0
Heterohelicidae						
Bolivinita quadrilatera (Schwager)	0	0	0	0	1	0
Buliminidae						
Bulimina sp.	0	0	0	0	3	0
Bolivina robusta Brady	0	3	2	0	0	11
Bolivina seminuda Cushman	0	0	0	0	0	7
Bolivina striatula Cushman	0	9	5	0	14	5

List of Foraminifera	Sample No.					
	Om-498	Om-584	0-2006	0-2007	0-2009	0-2008
Loxostoma karreriana (Brady)	1	99	1	0	3	61
Reussella spinulosa (Reuss)	0	20	1	0	5	9
Uvigerina cf. U.bifurcata d'Orbigny of Asano (1938)	0	5	0	0	1	1
Siphogenerina raphanus (Parker and Jones)	1	6	0	0	1	143
Angulogerina angulosa (Williamson)	0	1	0	0	0	0
Rotaliidae						
Discorbis bradyi Cushman	5	104	3	0	7	1
Discorbis imperatoria globosa Millet	1	8	0	3	35	3
Discorbis bertheloti (d'Orbigny)	0	0	1	0	0	0
Discorbis opercularis (d'Orbigny)	1	5	0	0	0	0
Discorbis orbicularis (Terquem)	0	9	1	0	0	0
Discorbis vilardeboana (d'Orbigny)	0	0	0	0	3	0
Eponides lateralis (Terquem)	0	5	0	0	0	0
Eponides cf. E.punctulatus d'Orbigny	1	17	127	5	14	1
Eponides umbonatus (Reuss)	0	1	0	0	0	0
Rotalia beccarii (Linné)	0	1	0	0	0	0
Rotalia japonica Hada	1	49	1	1	1	32
Rotalia nipponica Asano	141	1873	13	3	75	1
Rotalia nipponica Asano var.	7	94	0	0	0	0
Rotalia papillosa Brady	0	0	0	0	0	42
Cancris auricula (Fichtel and Moll)	0	0	0	0	0	4
Cymbaloporidae						
Cymbaloporetta bradyi (Cushman)	21	156	1	0	4	1
Cassidulinidae						
Cassidulina subglobosa Brady	0	1	0	0	0	1
Globigerinidae						
Globigerina bulloides d'Orbigny	0	6	2	0	25	7
Globigerinoides rubra (d'Orbigny)	0	4	0	0	0	0
Globigerinoides sacculiferus (Brady)	0	8	0	0	0	0
Anomalinidae						
Cibicides lobatulus (Walker and Jacob)	0	14	0	0	5	2
Cibicides refulgens (Montfort)	4	28	4	0	11	0
Hanzawaia nipponica Asano	0	4	0	0	2	34

* Species number of the Imperial Oil Co. laboratory.

This group of samples represents a miliolid-Rotalia-Elphidium faunule with subordinate Buliminidae and Discorbis and rarer arenaceous and polymorphinid elements; the pelagic element is poorly represented. A characteristic feature of this assemblage is the extreme rarity of Lagenidae and Cassidulinidae. A notable record is the finding of Rotalia nipponica Asano, formerly known from shore sands on the Pacific coast of Honshu and from the Pliocene of the Boso peninsula.

Compared with the shallow-water fauna of the Pliocene Haizume formation of Niigata Prefecture (1, 2, 3) the recent shallow-water assemblage contains the following warmer-water species not represented in the Haizume formation: Quinqueloculina parkeri Brady, Q. yabei Asano, Hauerina bradyi Cushman, Nodobacullariella insignis Brady, Vertebralina striata d'Orbigny, Parrina bradyi (Millet), Elphidium craticulatum (Fichtel and Moll), Loxostoma karreriana (Brady), Discorbis imperatoria globosa Millet. In general the Haizume assemblage has dominant Miliolidae and Anomalinidae with common Nonionidae and Textularia, and frequent lagenids, Cassidulina, Polymorphinidae and pelagic foraminifera; Rotalia and Buliminidae are rare.

The greater proportion of pelagic elements in the Haizume assemblage may indicate deposition farther from the shore than the Recent assemblage, and the absence of warmer water species suggests a lower thermal environment for the Haizume assemblage; these factors, in conjunction with the rarity of Rotalia and the more frequent occurrence of Lagenidae and Cassidulina in the Haizume assemblage, would suggest that the Haizume assemblage was developed in somewhat deeper-water and cooler conditions than the environment of the Recent assemblages studied.

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FORAMINIFERAL THANATOCOENOSES OF AGO BAY, KII PENINSULA, JAPAN

by

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ABSTRACT

Foraminiferal thanatocoenoses in Ago Bay are nearly similar to those in other bays and change in accordance with the change in oceanic conditions. In Ago Bay, the following assemblages are found:

(A) Globigerina assemblage. At the entrance of the bay; in other words, this assemblage is confined to the area within the open-sea water sphere of influence.

(B) Amphistegina - Elphidium crispum assemblage. This type exists near exists near the mouth of the bay and is found together with Rotalia rosea and Cibicides refulgens.

(C) Rotalia papillosa - Quinqueloculina lamarckiana assemblage. This type occupies the central part of the main bay and is, together with Textularia aff. T. foliacea, a characteristic species.

(D) Elphidium craticulatum - Textularia hauerii assemblage. Although (C) and (D) are not dominant assemblages, they exist in certain sections of the inlets, and are correlatives of Rotalia papillosa assemblages of Obama and Maizuru Bays.

(E) Trochammina assemblage. This is a dominant assemblage existing in the innermost part of the bay and is found together with Haplophragmoides and a small percentage of Nonionidae. Where this assemblage overlaps the Elphidium craticulatum - Textularia hauerii assemblage, Marginopora vertebralia and Trochammina nana become dominant species.

INTRODUCTION

This investigation was undertaken as a preliminary to the paleoecologic study of the smaller foraminifers. Fossil foraminiferal assemblages are composed of fossil remains representing animals which were living where they occur, as well as those which lived elsewhere but the remains of which were later carried and deposited in their present position. Those which remained intact and withstood dissolution with the passing of geologic time make up fossil assemblages. Therefore, in order to establish the relationship between fossil assemblages and the conditions surrounding their deposition it is necessary to take into consideration, besides the living foraminifers, tests of dead foraminifers deposited with them. I regard this treatment not as an ecologic study but rather as a thanatologic approach. Therefore, when dealing with fossil assemblages, I believe it more accurate to call the study, paleothanatology rather than paleoecology.

It was with the above concept in mind that this investigation was carried out.

Ago Bay is situated in the southeastern part of Kii Peninsula on the Pacific side of Japan. It is a drowned valley type of bay. This bay, together with Matoya Bay which adjoins it, is famous for its cultured pearls. Although the topography of the bay is complicated, the foraminiferal thanatocoenoses are distributed in fairly orderly fashion and to a certain extent can be correlated with those of other bays. According to data so far obtained concerning the distribution of foraminiferal tests on the bay floor, I believe it is possible, to draw fairly accurate conclusions regarding the oceanic conditions at the time of deposition from fossil thanatocoenoses. I plan to make an announcement of this point at some other time.

Moreover, almost similar results are being obtained through the study of molluscan thanatocoenoses which is being carried on in conjunction with the investigation of foraminifers (Miyadi and Habe, 1947).

METHOD OF INVESTIGATION

Bottom samples were taken at 49 stations within the bay in order to cover all of the different environments. Ekman-Lenz's Bottom Sampler was employed. Approximately 30 cc. of each of these samples was screened with a 200-mesh sieve. Foraminifers within the residue were sorted and the population counted. This information was listed, the percentage density of the dominant or characteristic species obtained, and the results entered on the map. A distribution curve of these species was plotted and the center of distribution of each species as well as the frequency distribution noted. In this way, it was possible to obtain types of thanatocoenoses characteristic of the various parts of the bay. The results are shown on the chart.

It is extremely difficult to analyze the relationship between these various groups and oceanic conditions. Moreover, such an analysis runs into the danger of being superficial. At present I believe that these various types of foraminiferal thanatocoenose exist merely as indicators of the combined result of the various influences of the oceanic conditions. I have no thought of analyzing the relationship between the various environmental physical factors and the assemblages. For reference and information, the depth and bottom temperatures at each station were taken and are shown in the following table. Bottom salinities (Cl o/o) range from 17.72 to 18.38, generally showing lower percentage at inner parts of the bay and pH varies from 8.10 to 8.40.

Station Nos.	Depth (m)	Bottom Temperature (C°)	Bottom Character
77	14.00	-----	Coarse sand
79	12.00	-----	Coarse sand
76	16.50	21.0	Fine sand
71	19.00	-----	Fine sand
70	30.00	-----	Rocky

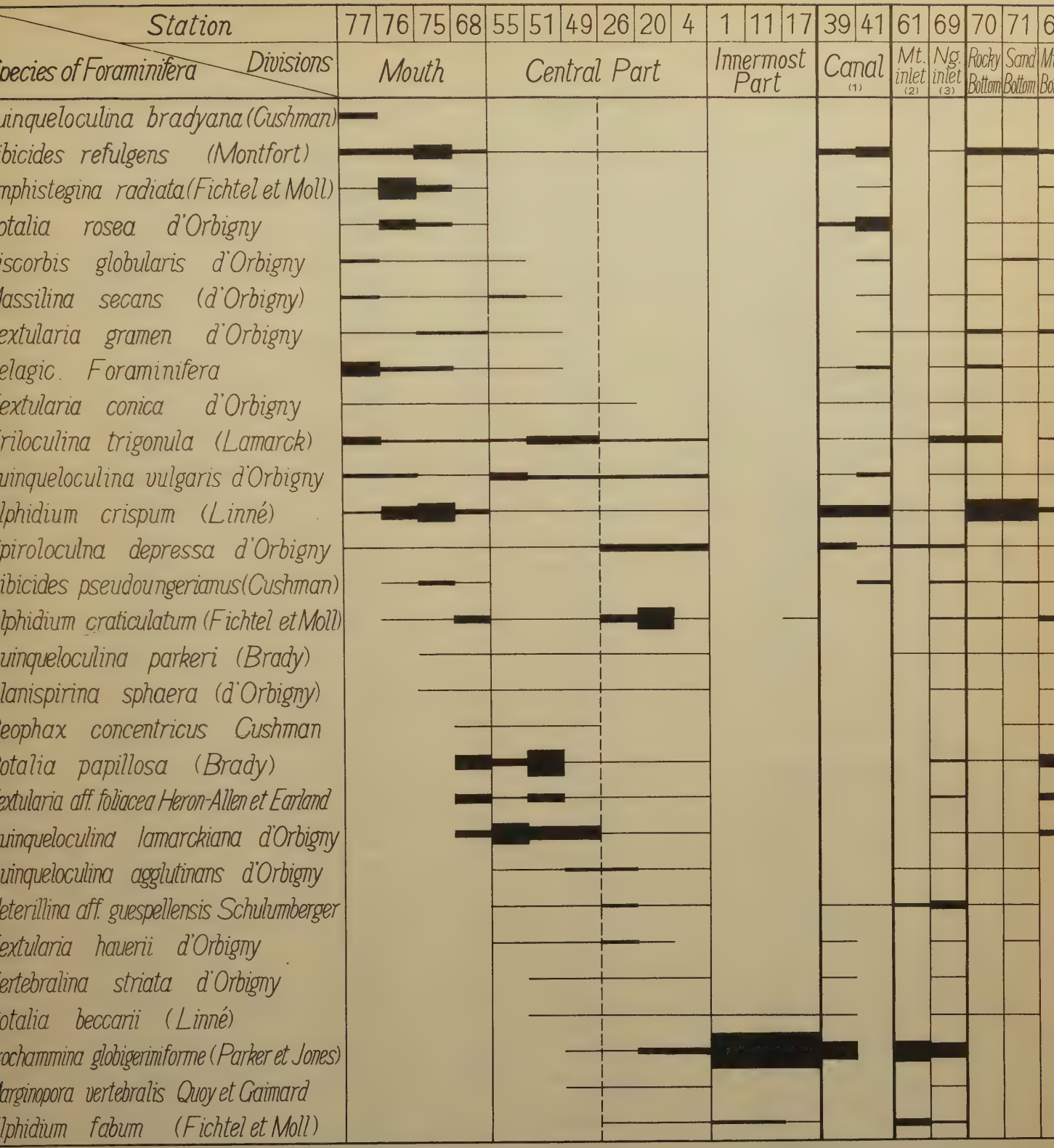

CHART I. SHOWING THE FREQUENCY OF OCCURRENCY OF CHARACTERISTIC SPECIES OF FORAMINIFERS.

The thickest line indicates the occurrence of the species with number of individuals of over 40 % and the finest line indicates less than 5 %. (1) Canal: inner part of canal at Funakoshi. (2) Mt: Matoya Bay. (3) Ng: Small inlet at Nagai-ura.

Station Nos.	Depth (m)	Bottom Temperature (C°)	Bottom Character
68	18.00	-----	Mud
75	12.00	-----	Fine sand
55	22.00	-----	Fine sand
51	25.00	-----	Fine sand
49	19.00	-----	Mud
47	13.00	-----	Mud
43	16.00	20.6	Mud
28	16.00	-----	Mud
30	10.00	-----	Fine sand
26	8.50	20.9	Fine sand with pebbles
52	18.00	-----	Mud
23	18.00	20.8	Medium sand
5	16.00	20.5	Mud
4	9.00	21.0	Silt
3	7.00	23.5	Sand with pebbles
2	8.00	21.2	Mud
1	3.00	23.2	Silt
6	10.00	21.0	Silt
7	5.00	21.9	Silt
8	7.00	23.6	Coarse sand
9	8.00	21.2	Silt
10	7.00	21.0	Mud
11	5.00	21.5	Silt
15	8.50	21.1	Medium sand with pebbles
20	5.20	21.2	Coarse sand
22	5.50	22.3	Mud
18	5.50	20.2	Mud
17	5.00	23.5	Mud
31	6.00	-----	Mud
33	14.00	21.0	Silt
34	5.50	-----	Fine sand
35	12.00	22.0	Mud
37	12.00	22.0	Mud
36	7.00	22.3	Mud
38	7.50	22.0	Mud
39	7.00	22.0	Mud
40	2.50	22.3	Mud
69	7.00	-----	Fine sand
41	2.00	23.0	Medium sand
45	7.00	-----	Silt
63	15.00	-----	Fine sand
61	9.00	-----	Silt
57	13.50	-----	Silt

(These observations were made at the time bottom sampling was done during June, 17-19, 1946).

POPULATION

The total number of individuals obtained from 49 stations in this bay is 43,346. The distribution of the number of foraminiferal tests showed nearly the same tendency as those for other bays; that is, the greatest numbers being at stations Nos. 76, 79 and 63 at the mouth of the bay, with counts of 7,200, 6,572 and 6,903 respectively, and gradually decreasing as the innermost section of the bay is reached, where the counts are 30 and 50 for stations Nos. 40 and 36 respectively. The counts for stations near Nos. 40 and 36 were found to be little more or less than 100-150. However, at Ago Bay the tendency of the number of tests to increase toward the innermost stations (as was the case in Obama and Maizuru Bays) was not found (Morishima, 1948). In all the bays the population is greatest at the mouth because it is at this point that the foraminifers living in the open sea and those living in the bay overlap. Furthermore, tests of planktonic foraminifers occur in the greatest numbers near the entrance of the bay where the bay water joins the open-sea water. Added reasons for this phenomenon are: (1) the supply of food at the border of bay and open-sea water is ample, and (2) the remains transported by the current are deposited here.

The distribution of the remains of the various species was worked out by determining one or more central points for each species, and with these as a working base the types of thanatocoenoses for the various locations were determined. The species showing the largest number of individuals is Elphidium crispum (Linné) with 2,432, followed in decreasing order by Trochammina globigeriniforme (Parker and Jones), Rotalia papillosa (Brady), and Quinqueloculina lamarckiana (d'Orbigny). Species belonging to the Nonionidae and Miliolidae are by far the most numerous while those belonging to the Lagenidae and Cassidulinidae are the least numerous of families that are usually found. On the whole, the average number of individuals per species is 231.4, which comes very close to the 228.9 for Obama Bay.

NUMBER OF SPECIES

There are in all 183 species, among which are 6 species of planktonic foraminifers and 24 of arenaceous foraminifers. The rest are benthonic calcareous species. The distribution of number of species and population is almost the same. In other words, stations at the mouth of the bay yield the greatest number of species -- 70 for station No. 76 and over 50 for the other stations near the mouth -- while those located towards the interior of the bay show counts which diminish in direct proportion to their relative distance from the entrance of the bay. The smallest counts are 6 species for station Nos. 17, 18 and 38.

The fact that the population as well as the number of species decreases as the inner parts of the bay are approached, holds entirely true in the other bays. This point is confirmed by remains taken at the inner part of the canal near Funakoshi which connects the ocean and the bay. Topographically, this region corresponds to the innermost section of the bay. Consequently, the population and the number of species at this point should show the smallest counts, but the construction of this canal connecting the Pacific and the bay resulted in the formation of an artificial mouth bay mouth. Here, the population numbered 1,595, the number of species was 73.

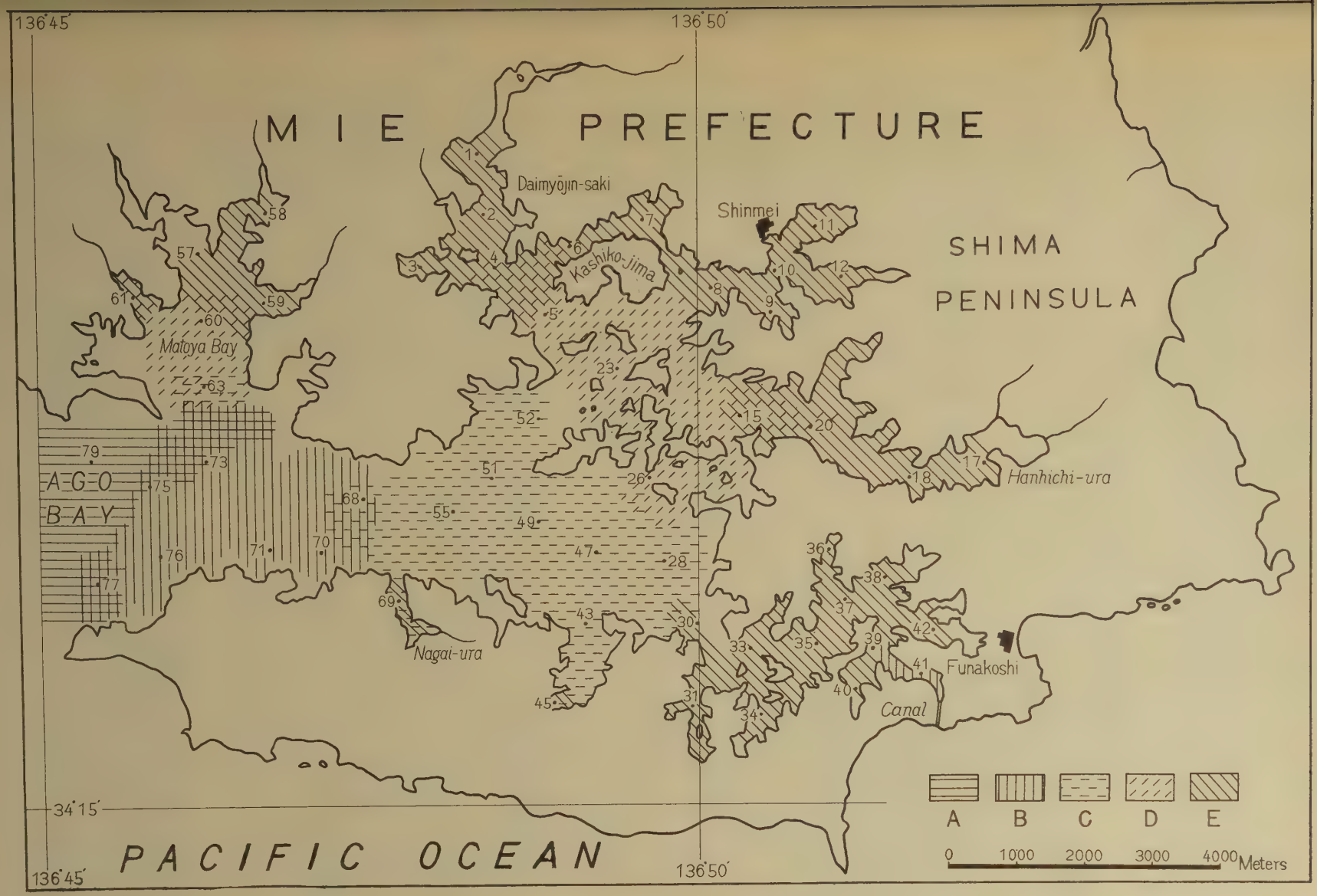

CHART 2. SHOWING AREAS OCCUPIED BY THE FOLLOWING FORAMINIFERAL THANATOCOENOSES:

A: Globigerina Assemblage.

B: Amphistegina - Elphidium crispum Assemblage.

C: Rotalia papillosa - Quinqueloculina lamarckiana Assemblage.

D: Elphidium craticulatum - Textularia hauerii Assemblage.

E: Trochammina Assemblage.

The number in the assemblage is dissimilar to that found in the inner parts of the bay, where it is centered around Trochammina but is the same as that characteristic of assemblages found at the mouth of the bay, and this shows the influence of open-sea factors. However, the influence of open-sea factors is not too strong as attested by the assemblages found at station Nos. 39 and 37. The collections at stations Nos. 38, 36, and 35 show the characteristic forms usually found in the inner parts of the bay.

TYPES OF FORAMINIFERAL THANATOCOENOSES

From the results of the distribution of foraminiferal tests at the various stations, the characteristic types of thanatocoenoses are determined (see chart 1).

Planktonic foraminifers, comprised mostly of Globigerina, and also including Globorotalia and Tretomphalus bulloides (d'Orbigny) showed the highest percentage, 23% in population, at station No. 76 and were confined to stations Nos. 79, 77, 75 and 63, at the mouth of the bay (Globigerina assemblage). As in the other bays, the planktonic foraminifers are deposited at points where the bay water and open-sea water overlap. Other dominant or characteristic species found only at the mouth of the bay are Amphistegina radiata (Fichtel and Moll), Elphidium crispum (Linné), Rotalia rosea (d'Orbigny) and Cibicides refulgens (Montfort) (Amphistegina - Elphidium crispum assemblage). Amphistegina radiata is also found in Maizuru Bay only at its mouth. Most of the other species are of the open-sea type. At station No. 41, near the canal at Funakoshi, Rotalia rosea, Amphistegina radiata and Elphidium crispum are also found, together with Rotalia beccarii (Linné), which is one of the characteristic forms found in the inner parts of the bay such as in stations Nos. 3, 7, 10, 18, 33 and 35. Furthermore, although not in conspicuous numbers, benthonic foraminifers of types usually found at the mouth and at the inner parts of the bay are found together. This fact means an invasion of open-sea water into this inlet.

Starting from the mouth and moving on towards the interior of the bay, Rotalia papillosa (Brady), Textularia aff. T. foliacea (Heron-Allen and Earland) and Quinqueloculina lamarckiana (d'Orbigny) are predominant, being particularly evident in the main section of the bay from station No. 68 to the mouths of the various inlets (Rotalia papillosa -- Quinqueloculina lamarckiana assemblage). Furthermore, toward the inner part of the bay, a less marked assemblage made up mostly of Elphidium craticulatum (Fichtel and Moll), Quinqueloculina agglutinans (d'Orbigny), Textularia hauerii (d'Orbigny) and Planispirina sphaera (d'Orbigny) is found (Elphidium craticulatum -- Textularia hauerii assemblage). Although not very prominent, this assemblage is found also at Maizuru at the mouth of the bay. At Obama a similar assemblage is found just a little way inside the entrance of the bay. It is believed that this comprises one of the clearly discernable types of assemblages common to these bays.

At the various inlets, Trochammina globigeriniforme (Parker and Jones) is by far the dominant species (Trochammina assemblage). Between the areas occupied by the assemblage of Trochammina globigeriniforme and those occupied by the assemblage of Textularia hauerii, a not too prominent group is represented by Marginopora vertebralis Quoy and Gaimard and Trochammina nana (Brady), etc. Trochammina globigeriniforme is a species which together with other arenaceous

forms (Hada, 1931, 1936, Asano, 1938) exists in the largest numbers in the innermost parts of the bays facing both the Japan Sea and the Pacific Ocean. In Ago Bay, there are many places where this species comprises over 80% of the population. Marginopora is fairly large-sized and its distribution is confined to a restricted area, though the number of individuals is by no means great. This is a prominent index species.

The above discussion covers distribution of the various assemblages for the main sections of the bay. However, when we consider the inlets attached to the bay; for example, Hamashima Inlet or Nagai-ura (see Chart 2), we find there, as shown in Charts 1 and 2, a mixture of assemblages peculiar to that section of the main bay where the inlet is located and the assemblage characteristic of that part of the inlet proper. For example, at station No. 69 at Nagai-ura, we find a mixture of assemblages, Heterillina aff. H. guepellensis (Schlumberger), Triloculina trigonula (Lamarck) and Rotalia papillosa (Brady), which correspond to those peculiar to the main part of the bay near station No. 68 and also assemblages characteristic of the inlets, Trochammina globigeriniforme and others. The same can be said for Hamashima Inlet. This phenomenon may result from lack of space for two different assemblages to exist separately.

As mentioned above, it is extremely difficult to determine the conditions which regulate the distribution of the various assemblages. Moreover, it is difficult to obtain a correlation between the distribution of species and the physical factors. Differences of various and naturally divergent conditions both at the entrance and in the interior parts of the bay may regulate the distribution of these different assemblages. And contrarily, it may be said that a knowledge of the various assemblages makes for an understanding of the various environmental factors. However, in the case of bays, it may be unquestionable that minute differences in salinity have great influence.

Up to the present, the relationship between the bottom character and benthonic foraminifers has been often discussed. The writer has also pointed out two or three instances of this relationship with reference to Obama Bay. It is believed that in a drowned valley type of bay, to which class Maizuru and Ago Bays belong, the effect of bottom character seems to be negligible. In all probability this is due to the fact that the bay is narrow and long, which in turn makes for strong influences of other environmental factors varying in different parts of the bays. As shown in Chart 1, there is hardly any difference in the assemblages obtained from three stations situated over rocky, sandy, and muddy floors.

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